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THE DESIGN OF DOMESTIC ELECTRIC COOKERS

By O. W. HUMPHREYS, B.Sc.

(Communication from the Staff of the Research Laboratories of the General Electric Co., Ltd., Wembley.)

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SUMMARY

The paper is devoted chiefly to those aspects of cooker design by which cooking performance is affected. Mechanical design is reviewed, but in much less detail, and mainly with the object of recording present practice.

The question of the indication of the "heating condition" of ovens is discussed, and the desirability is stressed of taking account of radiation as well as air temperature. Consideration is given to the problem of oven ventilation, particularly from the point of view of its effect on "steaming" at the vent. The advantages offered by thermostatic oven control are outlined and an attempt is made to forecast the changes, especially in connection with methods of heating and lagging, to which it is likely to lead.

The history of the development of boiling-plates is briefly reviewed, and the relative advantages and disadvantages of the various methods of construction commonly employed in this country are discussed.

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INTRODUCTION

During the last quarter of a century electric cooker development in this country has been proceeding along sound evolutionary lines, and until quite recently there has been but little tendency to break away from traditional practice. This does not mean that real progress has not been made. It rather implies that well-tried designs and constructional methods have been steadily improved as experience has shown the directions in which modifications could be introduced with advantage. In some other countries changes of a more revolutionary and experimental nature have been introduced from time to time, but it is a question whether all these innovations have been really advantageous.

How much longer the present policy will be followed by British designers is a matter of conjecture, but it is the author's opinion that the next few years will see important changes in connection with both external appearance and oven design. That some manufacturers are already being influenced by a demand for cookers whose lines are more in harmony with present-day conceptions of artistic form is evidenced by some of the new models which have recently been introduced, and with the growing popularity of thermostatic oven control new problems arise in connection with oven heating, ventila-

tion, and lagging, which may well result in a complete revision of present practice in these directions.

In this paper the author reviews present practice and endeavours to indicate the probable course of future development. A brief historical survey is included where it is felt that this will facilitate an appreciation of the problems which have now to be faced. Except where the contrary is specifically indicated, all references are to the practices adopted, or developments anticipated, in this country.

This review would be incomplete if no reference were made to the cookers working on the storage principle which have now been available for some years. These cookers were introduced on account of certain advantages which they offer to the supply undertaking from the load point of view, and can scarcely be discussed without consideration of supply conditions. Such a discussion falls outside the scope of the present paper, and as the cookers have already been described elsewhere* and the design problems involved are entirely different from those which arise in connection with the conventional type of cooker, it is not proposed to refer further to this interesting development.

FACTORS AFFECTING DEVELOPMENT AND DESIGN

Development and design are very markedly affected by many factors which have little, if any, effect on performance. Where, as is the case in this country, the majority of cookers are disposed of by simple hire or long-period hire-purchase, the supply authorities naturally demand a robust construction, which will ensure a long life and reduce the cost of maintenance to a minimum, and do not view with favour the incorporation of any new features which have not passed the most stringent tests. Frequent changes in external appearance are also deprecated owing to considerations of obsolescence.

In America, cookers are generally disposed of by direct sale or short-period hire-purchase. They are designed for a much shorter average life, and new features are continually added with the deliberate intention of rendering existing designs obsolete and encouraging their owners to obtain new, and more "up-to-date," models.

The supply authorities demand the lowest capital cost compatible with the provision of adequate facilities and satisfactory performance for their consumers, so that the hire or hire-purchase charges may be low and the number of cookers connected to their mains, and therefore their sales of electricity, may be as large as possible.

Building fashions must also be considered. Good appearance is essential when a cooker is to be installed in an attractively finished and fitted modern kitchen, and the small kitchens which are characteristic of present-day speculative building can frequently only accommodate cookers of very limited overall dimensions.

One of the great advantages of electricity as compared with the other sources of heat is its unobtrusiveness. The cook requires heat, ample in quantity and easily controlled, but the source of the heat does not interest her and the less conspicuous it can be made the better. Heating elements should preferably be arranged so that their presence may be ignored during cleaning operations, and every possible step should be taken to eliminate risk of accidental contact with live parts. With the high standard of reliability which has now been achieved, elements very seldom require replacement, and convenience and safety in daily use are more important than the very occasional saving of a few minutes.

High efficiency is desirable, but with the low rates at which electricity is now available simplicity, convenience, and a high standard of performance may be considered of even greater importance.

Finally, interchangeability of parts between different cookers greatly facilitates the task of the maintenance staff of the supply authorities.

GENERAL CONSTRUCTION FEATURES

The cooker consists of a framework on which are mounted an oven, a warming cupboard, a hob, one or more boiling-plates and a griller or griller-boiler, together with the necessary wiring, switches, and fuses. The oven, boiling-plates, and griller, together with their associated equipment and accessories, will be considered in detail in later sections of the paper.

Materials

The framework generally consists of a base and front frame of cast iron with sides and back of sheet steel. The oven and warming-cupboard linings are constructed of sheet steel, and the hob is of cast iron. The oven interior is preferably welded so that steam is prevented from escaping into the lagging, and the joint between the oven lining and the front frame should be made in a steam-tight manner. Warming cupboards should be watertight, so that liquids spilled therein may not find their way into the lagging. The oven door consists of a cast-iron door frame with inner and outer sheet-steel panels. Sometimes the steel door panels are replaced by glass. The warming-cupboard door, when provided, is of the drop-down type and consists of a single casting or steel pressing, or may employ a cast-iron frame and a single sheet-steel panel. The legs are usually of cast iron.

In America and on some parts of the Continent pressed-steel parts are extensively used in place of castings, but this practice, while it has not been entirely ignored, has not so far been at all widely adopted by British manufacturers. The advantages of pressed steel lie in the elimination of risk of breakage which is inevitably present with cast iron, its lighter weight, its smooth surface, which allows a very fine enamelled finish to be obtained, and the facilitation of assembly by mass-production methods which results from the accuracy with which pressed parts can be produced.

Castings, on the other hand, are more rigid and less liable to warp under mechanical or thermal stresses; they also offer the great advantage, which is of particular value during a period of rapid evolution, that they can be made from relatively inexpensive patterns which can be fairly readily modified, whereas steel pressings necessitate expensive tools which are not easily altered. The use of pressed steel introduces problems which do not arise with cast iron. In particular, special care in design is necessary to avoid distortion of such parts as hobs and front frames which are subjected to severe local heating and to steep temperature gradients. It is very important that

* *G.E.C. Journal*, 1932, vol. 3, p. 179; and 1935, vol. 6, p. 221.

a cooker should be designed to suit the materials of which it is to be constructed and that a design prepared for cast iron, for example, should not be used for pressed steel.

Finish

All structural metal parts, whether of cast iron or of sheet steel, are now almost invariably finished in vitreous enamel. This finish is attractive in appearance, very easily cleaned, very resistant to corrosion, and reasonably robust. A mottled-grey finish has been proved by experience to be the most durable, and therefore the best suited for use on cookers let out on simple hire. Some relief is usually given by the provision of a white panel in the oven door. Attractive colours are also available. If an acid comes into contact with the surface of ordinary vitreous enamel the glaze is quickly destroyed. Acid-resisting and acid-proof enamels can now be obtained and are commonly employed for hobs. Some manufacturers extend their use to all cast parts of the structure. The chief weakness of vitreous enamel is that once damaged it cannot be repaired, and to restore the original finish the affected part must be completely stripped and re-enamelled. This is a handicap to the manufacturer, and still more so to the supply authority that is faced with the necessity of reconditioning cookers returned from hire.

For parts such as oven interiors which are subjected to severe changes in temperature, vitreous enamel is not so satisfactory as it is for the external parts of the cooker, as "crazing" is liable to occur. Heat- and corrosion-resisting alloys which would not require any protective coating are available and would be more suitable, but their use would at present involve a substantial increase in cost.

Wiring, Switches, and Fuses

The majority of modern cookers have a wiring compartment on the right-hand side. The front frame casting extends over this compartment and carries the switches, of the reciprocating rotary type, in a vertical line. Local-circuit fuses are generally provided in the circuits supplying the oven, the griller, and each boiling-plate, and access to them is gained either by removing a panel above or below the switches in the front frame or in the side plate, or by removing the whole of this plate. Terminals are provided for the reception of the supply and earth wires.

Electrical connections are usually made with bare or asbestos-covered copper wire. It is necessary to ensure that the covering used has adequate insulation resistance when damp, or alternatively to prevent contact between wires which may, with any of the possible switch positions, be of different polarity, or between the wires and the cooker body. In no circumstances should connecting wires be allowed to come into contact with slag-wool lagging. The temperature to which asbestos-covered leads can safely be subjected may be lower than that which is permissible for bare wire, owing to the presence in the covering of materials which accelerate the oxidation of copper.

Earthing

It is most important that adequate steps be taken to ensure the proper earthing of all metal parts of the cooker which may accidentally become alive. Owing to the insulating properties of vitreous enamel, mechanical contact between the various parts is not sufficient. All parts of the cooker framework, exposed metal parts of fixed heating elements, and earth contacts associated with plug-in elements, should be bonded together and to the earth terminal by means of a copper wire or strip of suitable cross-sectional area. Bonding should also be provided where necessary between exposed metalwork and the earth pin on plug-in elements.

OVENS

Systems of Heating

Any of the normal methods of heat transfer—radiation, conduction, and convection—may be employed for cooking purposes according to the results desired. The main difference lies in the degree of uniformity of the cooking between the outer surface and the centre of the charge. Whichever process is employed, the heat reaches the centre of the food by conduction from its surface. The degree of uniformity depends on the temperature gradient, which, in turn, is controlled by the conductivity of the food and the rate of absorption of heat at its surface. Generally speaking, radiation permits the greatest concentration of energy at the surface, and is therefore employed for such processes as toasting and grilling where a well-cooked exterior, and lightly-cooked interior, are required. Convection heating, with air at relatively low temperature, is preferred for such processes as the baking of cakes, where the highest possible degree of uniformity is desirable.

It is possible so to design an oven that heating is effected either by convection only, or by a combination of radiation and convection. Entirely convective heating is only obtained when the temperature of the surfaces bounding the cooking space is equal to that of the surface of the charge. This condition is very nearly complied with by the use of low-temperature elements, situated at the sides of the oven behind baffles which screen them from the cooking space and which form, with the oven lining, ducts through which the oven air can circulate freely.

If free circulation is not permitted, the air in the duct, and therefore in the baffle also, will reach a temperature much in excess of that of the air in the cooking space, and food placed in the oven will be heated partly by radiation from the surface of the baffle. Elements are sometimes fitted beneath a perforated baffle situated in the bottom of the oven. In such a case considerable care must be exercised in determining the positions of the perforations if convection heating is the object.

The highest proportion of radiant heating is obtained from open-coil elements radiating directly to the cooking space. The only common example of this arrangement is the top element in top-and-bottom-heated ovens.

A system of almost entirely convective heating operating on lines similar to those described above is employed by one British manufacturer, but, in general, cookers intended for the home market employ heating systems intermediate between the two extremes. In many instances heating is by a combination of radiation and convection from the walls of the cooking space, which are themselves heated by elements clamped to or embedded in them, or by radiation from open-coil elements

situated behind or below them. In other cases the heating surface is that of some form of sheathed element which is situated inside the cooking space.

It is shown later that where an oven is to be thermostatically controlled, convective heating offers very definite advantages, but with manual control the choice of the heating system is largely a matter of personal taste. An experienced cook can produce excellent results with any system provided it is soundly applied, but a change from one system to another often involves changes in cooking methods which embarrass those who are less skilled, and earn for the newly adopted system a reputation for difficulty which is not deserved.

Ovens employing side heating only, or side-and-bottom heating, require a somewhat different cooking technique from those which are equipped with top and bottom elements. The chief difference lies in the method of control. With no top heat, control is by a single switch offering three alternative element connections, of which two only ("high" and "low") are at all commonly used. In top-and-bottom-heated ovens, on the other hand, the top and bottom elements are frequently controlled by separate 3-heat switches, and the top element is also used for grilling. Of the nine alternative element connections which are available, five are quite commonly used. The close control of the heating conditions in the oven which is thus made possible is of value to the expert cook, but to the average cook the selection of the best combination of switch positions presents some difficulty and is only learned as a result of considerable experience, or very detailed instructions.

Control is sometimes by means of a single switch offering three degrees of heat for oven cooking, in which case grilling facilities are provided elsewhere, or alternatively the element connections for the various switch positions may be as follows: (1) Top element on full, for grilling and quick browning. (2) Top and bottom elements on full, for preheating and commencing roasting. (3) Half bottom element on, for all other purposes. Provided that the "low" loading is determined with care, this arrangement can give excellent results, and it makes the oven as simple to use as one with side, or side and bottom, elements.

Types of Elements

Oven elements may be classified as follows:—

(1) Those which are permanently wired and situated either (*a*) between the walls of the oven and the cooking space, or (*b*) outside the oven interior.

(2) Those which are arranged to plug-in in one of the following positions, and are withdrawable either from inside the cooking space or from the back of the cooker: (*a*) inside the cooking space, (*b*) between the walls of the oven and the cooking space, (*c*) in cavities in the oven walls.

Elements in Class 1(*a*) usually consist of heating coils mounted in grooved ceramic formers. They are associated with a lining to the cooking space which is removable for cleaning, and for access to the elements, in one or more pieces.

Arrangement 1(*b*) offers an entirely unobstructed, and therefore easily-cleaned, oven interior, with elements so completely hidden that the user need never be aware of their position; but this arrangement may involve some difficulty when element replacement becomes necessary. Wound mica elements are attractive for this purpose, but the wire temperature must be kept low to avoid dehydration of the mica, and very careful design, particularly in connection with the clamping system, is therefore necessary.

Where elements are so situated that cleaning can be facilitated by their removal, the plug-in arrangement has much to commend it. Very many types have been fitted from time to time. For use inside the cooking space [Class 2(*a*)] some form of metal-sheathed element is essential, the coils being insulated from the sheath by ceramic formers, or by being embedded in refractory cement. The second subdivision of Class (2) includes open-coil elements mounted in frames equipped with plug connections, which give a performance identical with that of elements in Class 1(*a*). Another type in this category consists of heating coils mounted in refractory tubes in a ventilated vitreous-enamelled housing. These elements are mounted behind vitreous-enamelled guards which are arranged to permit very free air circulation and so give the nearest approach to purely convective heating.

One example of Class 2(*c*) consists of heating coils threaded through porcelain blocks which slide into channels in the oven lining. This type is removable from the back of the cooker, but only needs to be removed in the event of failure.

Plugs and sockets must be kept as cool as possible and must be made from metals which will withstand without loss of contact pressure the temperature to which they are subjected, and which will not "seize" if the elements are not withdrawn for long periods.

No difficulty should be experienced in so designing oven elements that the wire temperature is below 800° C. with the oven at its highest cooking temperature. Since at this temperature the life of the element should be practically indefinite, it is not worth while to make any appreciable sacrifice in other directions solely to ensure very quick element-replacement in the event of failure.

Dimensions and Loadings

The enormous variety of sizes of ovens, and the wide variations in the densities of loading, are clearly shown in Fig. 1, in which the relation between volume of cooking space and loading is plotted for the products of 12 manufacturers. The density of loading varies from 0·515 to 1·12 watts per cu. in. Similar diversity is found in oven dimensions, and while in the majority of cases depth is greater than height, and greater than, or equal to, width, there are quite a large number of exceptions.

Ventilation

With electrically-heated ovens it is not necessary to maintain a circulation of air through the oven, but some provision for the removal of the large quantity of water which is evaporated during most baking operations is required. Usually a single opening is provided either at the top or at the bottom of the oven door, at the back of the oven, or between a part of the door frame and the front frame of the cooker. Adjustable dampers are sometimes fitted to enable the area of the vent to be controlled.

Some manufacturers provide adjustable vents in both the top and the bottom of the oven door, thus permitting through ventilation, and in one instance permanent openings are provided in the bottom of the oven beneath the heating elements, and in the top of the oven.

When a single vent is provided, and the oven door fits really well, so that there is no possibility of air entering the oven through the door joint, evaporated water passes through the vent in the form of steam. If immediately it leaves the vent it comes into contact with cold air, it condenses into a cloud of visible water vapour. If the air is warmer the steam has time to diffuse before it condenses, or is absorbed by the air, and its presence is not noticeable.

When through ventilation is permitted, either intentionally by the provision of two vents, or unintentionally because the fit of the door is not perfect, the amount of air passing through the oven may be sufficient to absorb the water which is evaporated. Some condensation may occur as the air cools, but the velocity of the water-laden air as it leaves the vent is much higher than that of the steam in the case previously considered, and the opportunity for diffusion and partial re-absorption by the general air of the room is therefore much greater.

The action of through ventilation in reducing condensation around the vent can often be demonstrated by selecting an oven which does not normally exhibit this effect, and packing the joint between the door frame and the front frame of the cooker with paper. By this means accidental ventilation is eliminated, and condensation will frequently commence.

" Steaming " at the vent is frequently regarded as indicating a defect in the cooker. Actually, as has been shown, it may merely arise through the use of a particularly well-fitting door, and the presence or absence of this phenomenon has no bearing whatsoever on the quality of the cooking. Vents are provided to enable steam to escape from the oven. Whether this steam condenses just outside the vent, or on the walls of the kitchen, or is absorbed by the air in the kitchen, is of but little importance.

Internal Fittings

Ovens are supplied complete with wire shelves and shelf-runners. The latter may consist of special frameworks which clip on to the side walls of the oven, or they may be formed integrally with the walls. In either case the combination of shelf or runner should be such that the shelf can be partially withdrawn without tilting. Pressing the runners into the oven walls or element guards reduces the number of removable parts and facilitates cleaning.

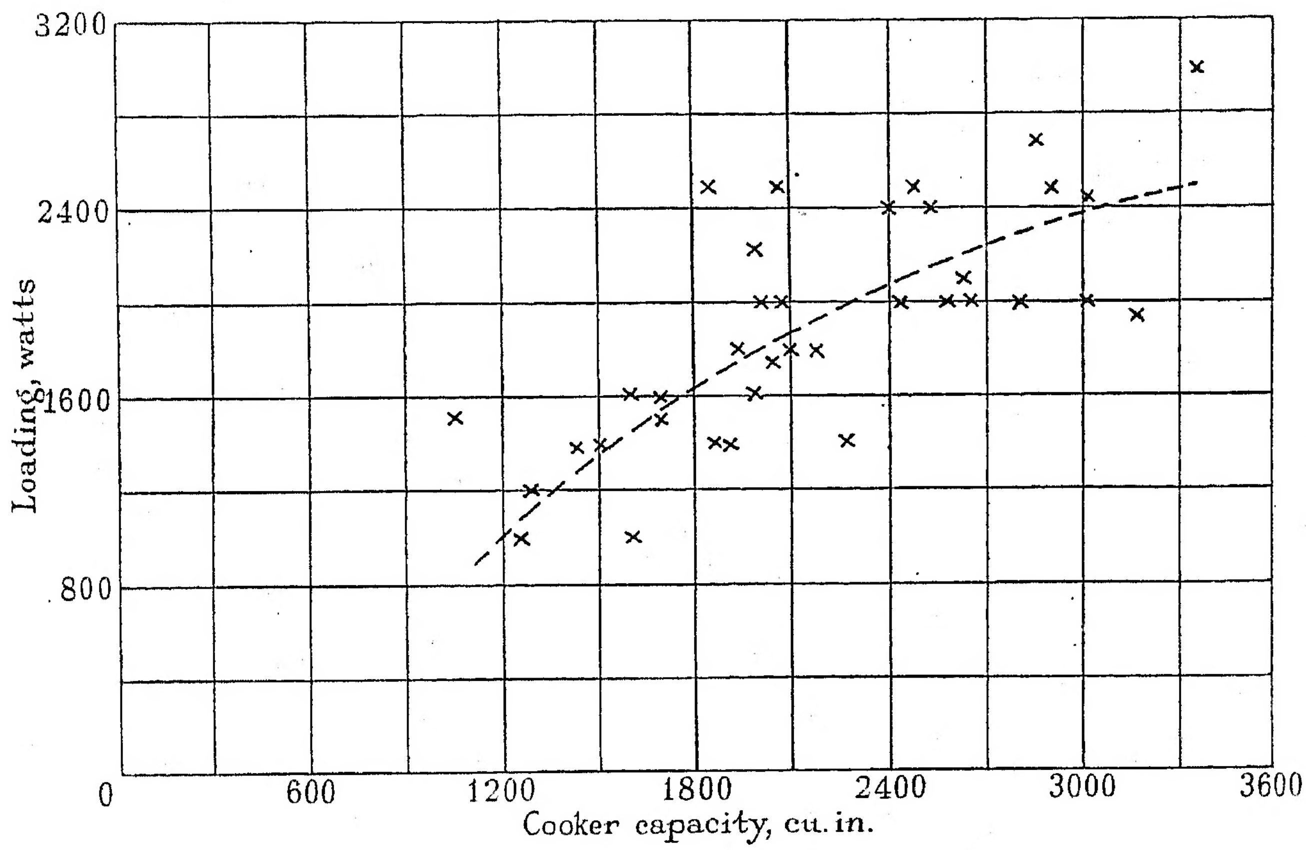

Fig. 1.—Relation between oven loading and volume of cooking space.

Lagging

Materials.

A perfect oven-lagging material would possess the following properties: (1) Low thermal conductivity. (2) Maintenance of condition and properties when repeatedly heated to the maximum temperature reached during cooking, or when the oven is accidentally overheated. (3) Ease of application. (4) Freedom from corrosive effect on the materials with which it comes in contact. (5) Freedom from " settling " when subjected to vibration. (6) Low cost.

Slag wool, which is at present very widely used, fulfils many of the requirements. Its thermal conductivity is very low and it can be easily and quickly packed into a space of any shape; it has good heat-resisting properties, and its cost is very low. On the other hand, it is fairly strongly chemically reactive, and it is essential that all metal surfaces with which it comes in contact should

be adequately protected, as, for example, by vitreous-enamelling. If not very tightly packed, slag wool tends to disintegrate and " settle " under vibration, and it is not a very pleasant material to handle. Rock wool, which is generally similar to slag wool, but more free from corrosive constituents, is commonly used in America and to some extent in this country.

Glass silk possesses all the desirable features of slag wool and is at the same time non-corrosive, much more pleasant to handle, and, on account of the long threads in which it is produced, less liable to settle. Unfortunately its use in a highly competitive market has so far been excluded by its relatively high cost.

Insulating materials made up into slab form of such shapes that the complete lagging of the oven can be achieved by the use of 6 slabs, reduce the labour involved in applying the lagging to a minimum, ensure uniformity of insulation, and completely eliminate settling. The oven must be specially designed, however, to enable slabs of simple geometric shape to be used.

A further alternative is aluminium foil arranged round the oven interior in a number of layers separated by air spaces of about 1 cm. thickness. In this way a lagging effect at least equal to that given by a similar thickness of the best of the more conventional types of lagging material is obtained. The cost of the foil is very low, but this may be offset by the cost of spacers and of labour. Complete freedom from settling or corrosion troubles is assured. On account of the very low heat capacity of the foil, preheating times are reduced and, as is shown in another part of this paper, thermostatic control is simplified. Lagging spaces must be of simple shape. Various methods of spacing the foil, some of which are covered by patents, have been proposed.

Thickness.

As the thickness of the lagging on an oven is increased the heat-loss to the atmosphere from the outer walls of the cooker is reduced, and the loss by absorption in the lagging material becomes greater. From the point of view of economy in energy consumption, it has been shown experimentally that lagging thicknesses considerably greater than those now commonly used would be well justified. For example, the energy consumption during the cooking of a series of meals in an oven lagged with 3 in. of slag wool was found to be approximately 25 % lower than in an identical oven with only 1 in. of lagging.

Running cost is not the only factor to be considered however; account must also be taken of capital costs, and the limitations on overall dimensions imposed by considerations of space, and in view of the low prices at which electricity is now generally available these latter considerations are undoubtedly of the greater importance.

Temperature

Indication.

The quantity which determines whether an oven is in suitable condition for the carrying-out of any particular cooking operation is the rate at which heat would be transferred to the surface of a charge placed therein. For brevity this quantity will be referred to as the " heating condition " of the oven.

Before the days of electric cooking the cook usually determined heating condition by inserting her hand into the oven, or by other primitive, but not therefore necessarily unsatisfactory, methods. With the introduction of electric heating, precise control of heating condition became possible and the desire for some indication of that condition followed naturally. The method adopted was to fit, usually to the door of the oven, a thermometer calibrated in terms of oven temperature. Owing to the necessity of protecting the thermometer from damage, and of avoiding encroachment on the cooking space, the bulb of the thermometer (or the bimetal coil, if a heat indicator of that type be used) is frequently recessed into a cavity formed in the door lagging. The temperature in this cavity is inevitably lower than that of the main body

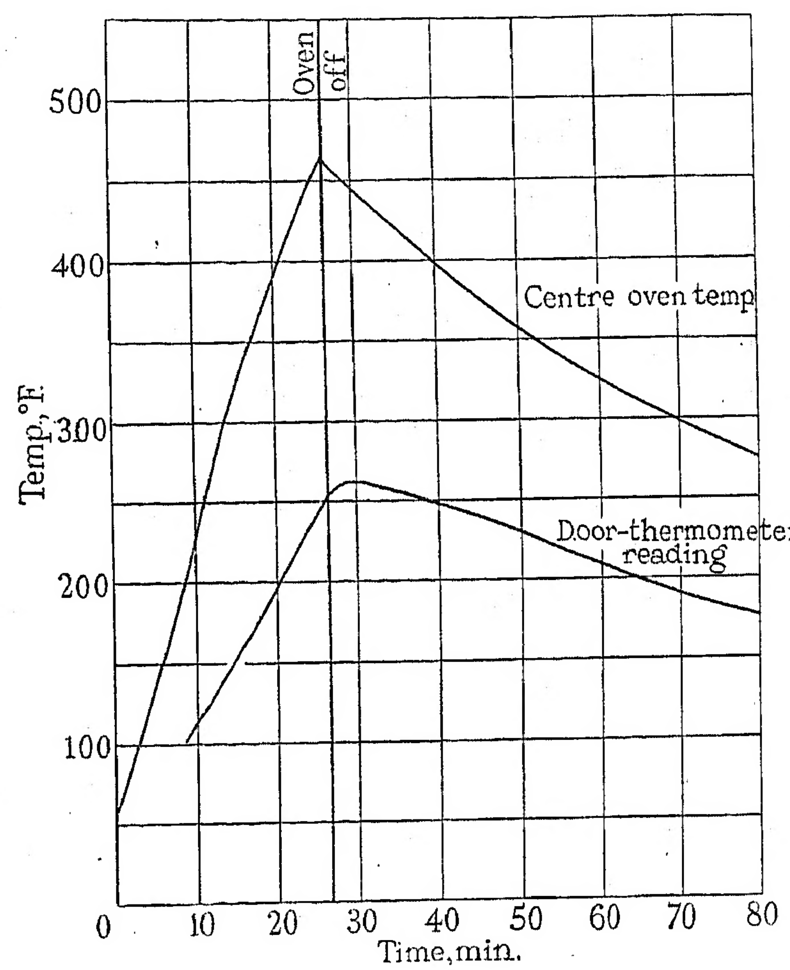

Fig. 2.—Relation between centre oven temperature and door-thermometer bulb temperature.

of air in the oven, but to an extent which depends on a variety of circumstances and varies between quite wide limits.

Figs. 2 and 3 show the relation between true centre oven temperature and the thermometer indication for one modern cooker which was fitted, for the purposes of the experiment, with a thermometer calibrated to read true bulb temperature. Fig. 2 records the results obtained when the heating elements were switched off immediately the oven temperature reached 450° F. (232·2° C.), while Fig. 3 shows the effect of switching to " low " for a period of 1 hour before switching off. It is not suggested that the discrepancy is always as great as indicated in the Figures, but, in a greater or lesser degree, it is inevitably present.

It is clear from the Figures that any attempt at a division of errors is out of the question as those remain-

ing would be so great as to render the indication of the thermometer practically valueless at all times.

As an accurate knowledge of temperature is of the greatest importance at the time that the food is inserted in the oven, it is customary so to calibrate the thermometer that it indicates true oven temperature during initial heating from cold. Thereafter the thermometer readings bear an indeterminate relation to oven temperature and are of little real value, but this is only a serious inconvenience when it is desired to carry out in succession two cooking operations requiring substantially different temperatures.

Careful attention must be given to the mounting of the thermometer in the oven door, as seriously inaccurate readings will be obtained unless an airtight seal is provided between the thermometer stem and the oven interior, to prevent the passage of cold air from the outside atmosphere over the bulb.

It is essential that thermometers should be able to withstand, without mechanical damage or change of calibration, the highest temperature that the oven may reach if it is inadvertently left in circuit at maximum loading. With the bimetallic type of indicator this necessitates special care in the choice of the bimetallic combination, since some materials which would be entirely satisfactory if heated through the range of temperature normally used in cooking, would become over-stressed if heated to the maximum temperature obtainable with full oven loading.

Significance.

The rate at which heat is transferred to a charge in an oven depends in part on the air temperature, but in part also on the temperature of the surrounding surfaces from which it receives heat by radiation. It is therefore impossible to define heating condition completely in terms of air temperature, and this difficulty is reflected in the widely differing temperatures which are recommended by various cooker manufacturers for the same operation. If one goes outside the field of electric cooking and includes ovens heated by gas or solid fuels, the variations become still more marked.

In any individual cooker a knowledge of air temperature only enables a previously-obtained heating condition to be repeated, but with every change in the proportions of radiant and convective heating the relationship between air temperature and heating conditions is altered, and revised cooking instructions become necessary. So long as this state of affairs exists, the preparation of cookery instructions which will be applicable to all types of cooker is out of the question. The difficulty could be overcome by calibrating the heat indicator in terms of heating condition instead of oven temperature, with a scale of "heat numbers" in place of degrees Fahrenheit. This is the common practice with thermostatically-controlled gas cookers, and has been adopted by some manufacturers of thermostatically-controlled electric cookers, but as there is at present no agreed standard scale of heat numbers definitely correlated to heating condition (the gas industry uses at least 6 different scales) the limitation of the present arrangement is perpetuated. It is suggested that the development of a standard scale would be of great value. It would facilitate the change from one type of cooker to another, and would also greatly increase the number of recipes on which users of any particular cooker could draw. Associated with it there would have

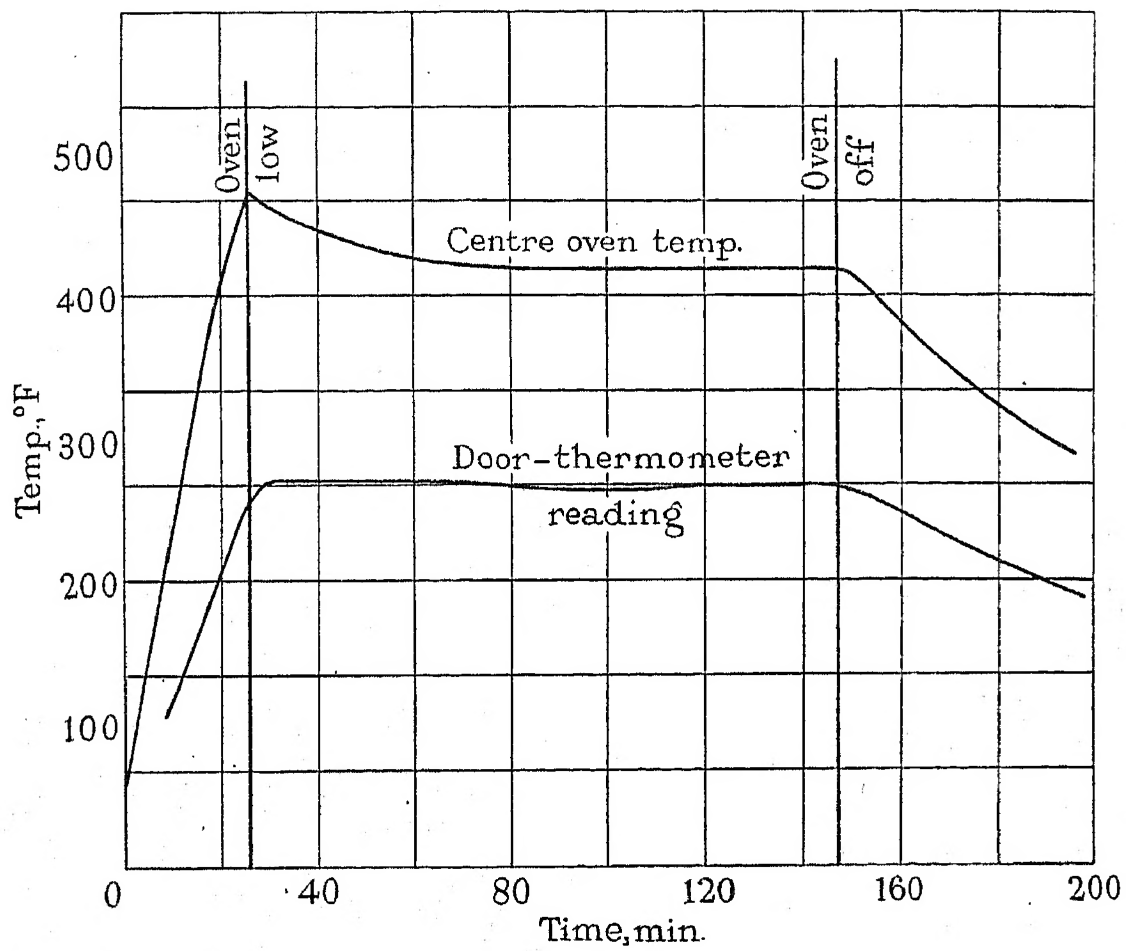

Fig. 3.—Relation between centre oven temperature and door-thermometer bulb temperature.

to be a standard method of determining heating condition. A. H. Barker,* during the course of an experimental investigation of solid-fuel-heated cooking ranges, developed a calorimetric method of determining the rate of heat transmission to a charge in the oven, and carried out a preliminary research concerning the rate of transmission required for various cooking operations. Much experimental work would undoubtedly be necessary to determine the applicability of any methods which might be proposed to all types of cooker under all conditions. In the meantime it might be possible to fix a scale in terms of various cooking processes—No. 2, for example, corresponding to the heating condition required to bake milk puddings, and No. 7 to that required for roasting beef, etc. This procedure has already been applied by one manufacturer of thermostatically-controlled electric cookers. The correct calibration for each type of cooker has at present to be determined by actual cooking tests. This method may be a little cumbersome, but it at least has the merit of being certain.

Measurement.

A word concerning the measurement of oven air temperature for experimental purposes may not be out of place. Owing to the effect of radiation special precautions have to be taken to ensure that the reading given by a pyrometer is not higher than that of the air. Some years ago the author carried out a series of measurements using four types of pyrometer, as follows: (*a*) A thermocouple attached to two very thin copper discs of 2 in. diameter welded together at right angles. This arrangement was on the lines previously suggested by E. Griffiths,† but with his single disc replaced by the two discs to eliminate the effect of the orientation of the disc with respect to the elements. (*b*) A thermocouple consisting of 0·8-mm. diameter copper and eureka wires with the junction between them welded. (*c*) As (*b*), but employing 0·1-mm. diameter wires and with the welded joint as small as possible. (*d*) A resistance thermometer made from 0·03-mm. diameter platinum-iron wire wound on a vacuum-lamp frame.

Comparative readings were obtained with all these instruments in an oven fitted with top and bottom elements, the top one being, as usual, unshielded. The readings obtained with the four pyrometers, in the above order were as follows: 469° F. (242·8° C.), 417° F. (213·9° C.), 405° F. (207·2° C.), and 384° F. (195·6° C.). As all the pyrometers had a very low heat-capacity the question of lag of the pyrometer temperature behind the air temperature does not arise, and the lowest reading must be the most accurate. Measurements were also made in a side-heated oven with protected elements using pyrometers (*a*) and (*c*) only. In this case the radiant heating was greatly reduced and the difference between the readings was only 14 deg. F. (7·8 deg. C.). From this it is concluded that in the absence of completely-exposed elements the readings of a fine-wire couple will be sufficiently accurate, but that a resistance thermometer, such as is described above, should be used when such elements are fitted.

* Special Report No. 4 of the Fuel Research Board.
† *Journal I.E.E.*, 1921, vol. 59, p. 367.

Thermostatic Control

Effect on cooking performance.

Thermostatic oven control received some consideration in the very early days of electric cooking, and some 2 000 thermostatically-controlled electric cookers were made by one British manufacturer. A mercury thermometer, with sealed-in contacts, served as the thermostat, the circuit being controlled through the medium of a relay. Generally speaking, however, it must be admitted that it is only during the last few years that thermostatic oven control has received serious attention in this country. In America it has been well established for many years. The public has become so used to thermostatic control, through its very successful exploitation in connection with gas cookers, that there is very little doubt that the demand for it on electric cookers will grow rapidly now that it has become available. It may be argued, apparently with a fair amount of justification, that the manual control of electric ovens is so simple that the thermostat cannot possibly have much to offer, but experience shows this view to be mistaken.

The chief advantages, especially when cooking has to be fitted in with other household duties, are undoubtedly the removal of the risk of overheating during the preheating period and of all need for attention while cooking is in progress. In addition, cooking is simplified and better results are likely to be obtained. The reasons for this are as follows: (1) By adhering to predetermined thermostat settings uniformity of results on different days is assured. (2) With certain long-period cooking operations, especially those requiring a low temperature, it is sometimes difficult with manual control to maintain the desired temperature with accuracy throughout the whole period. Thermostatic control eliminates this difficulty. (3) Thermostatic control removes the difficulty already referred to in connection with oven thermometers so far as the carrying-out in succession of cooking operations requiring different temperatures is concerned.

An important difference between manual and thermostatic control is that whereas with the former cooking is usually carried out with a falling temperature, with the latter the temperature is maintained at a steady value throughout the whole operation. As a result of this, the oven temperatures required with thermostatic control are lower than those which are recommended for the *commencement* of cooking with manual control.

Technical considerations affecting design of thermostat.

Great care must be exercised in choosing a thermostat to ensure that it is really suitable for the particular cooker to which it is to be fitted, since different systems of oven heating, and methods of applying thermostatic control, may call for widely differing characteristics in the control instrument. The usual method of application is for the whole of the preheating load to be under thermostatic control throughout the entire cooking period. Occasionally this load is reduced, either automatically when the thermostat first cuts out, or by the operation of a switch when the food is put into the oven; and in some instances a small proportion of the total load is left in circuit continuously, the balance being controlled by the thermostat.

It is of the first importance that, once the thermostat has commenced to operate, cooking results should be independent of the time at which the food is inserted in the oven. To achieve this, the amount of heat absorbed by the charge must be the same whether the charge is inserted immediately after the first cut-out of the thermostat or at any later time. At first sight it might appear that this condition would be met provided the change in oven temperature between opening and closing of the thermostat was small. With an oven heated entirely by convection, and the rate of transfer therefore depending only on air temperature, this would be true, for a small change in temperature would represent a very small alteration in heating condition. If radiation plays any important part, however, it is no longer the case, for since the radiating surfaces are usually associated with bodies of relatively low heat capacity, they change in temperature very rapidly when the thermostat operates, and in consequence the heat-transfer by radiation varies between wide limits in a very short space of time. Consequently the rate of heat transfer is much greater during the " on " period than it is during the " off " period, and the only way to ensure the same total heat-transfer during a given time is to employ a thermostat which operates with a very short time cycle. A further objection to a long time cycle is that it may lead to overheating, and consequent burning, of the parts of the charge in closest proximity to the radiating surfaces. With the general run of present-day cookers this cycle should not much exceed 5 min., and a shorter period is frequently advantageous. Even with so short a cycle the cooking of such items as small cakes will not occupy a sufficient number of cycles for the results to be independent of the time of insertion, and more uniform results are frequently obtained by slightly increasing the initial temperature and switching off when the charge is placed in the oven.

With well-lagged ovens, such as are commonly made in this country, the rate of cooling is so low that a short time cycle involves very close control of air temperature, and a very sensitive thermostat (i.e. one with a very small temperature " differential ") is therefore required. A small differential usually implies low contact-pressure, and a short time cycle involves a very large number of operations. With a time cycle of 4 min., for example, and the oven in use, in an extreme case, for 2 hours a day, the number of operations would be about 11 000 per annum, or anything from 50 000 to 100 000 during the life of the cooker. Very careful design and testing is necessary to ensure that the instrument will not only function satisfactorily for the required number of times as a switch, but that it will do so without serious change in operating temperature or differential.

The nature of the problem will be appreciated when it is realized that with a thermostat of the type which is actuated by the differential expansion of a rod and tube a change in temperature of 10 deg. F. (5·6 deg. C.) only produces a differential expansion of about 0·001 in. Conversely a change of 0·001 in. in the relative lengths of the two members results in a change of about 10 deg. F. in operating temperature. Great care is therefore called for, both in design and in choice of materials, to eliminate alterations in dimensions such as may occur in metals owing to annealing or to creep under mechanical load, and in insulating materials owing to shrinkage under the influence of heat.

Some types of thermostat employ bearings which are exposed inside the oven, and in such cases the effect of carbonized fats, etc., on the free working of the instrument requires consideration.

Effect of thermostat position on performance.

The performance of a thermostat is very largely influenced by its position in the oven. The best position depends on the type and disposition of the heating elements, and the system of ventilation employed, and must be determined experimentally. Fig. 4 shows the effect of placing the thermostat too close to the elements. The temperature of the air surrounding the thermostat rises

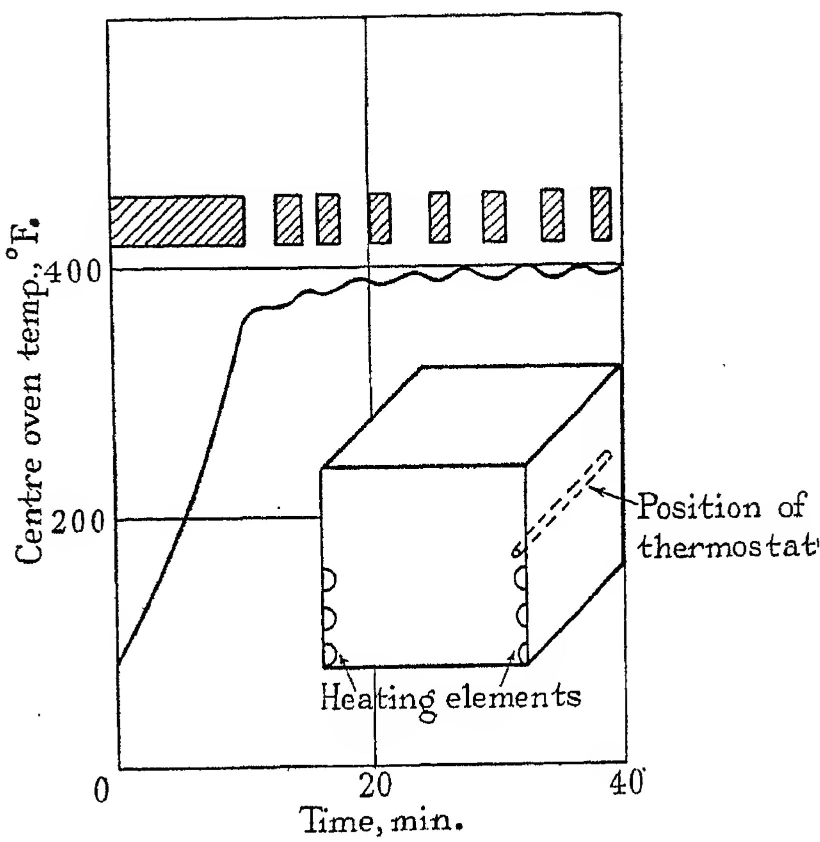

Fig. 4.—Effect of thermostat position on control of centre oven temperature: thermostat too near heating elements.
Shaded portions indicate periods during which thermostat was closed.

more quickly than that of the air in the centre of the oven. Consequently the first cut-out occurs before the final temperature has been reached in the centre of the oven, and several further cycles have to be completed before steady conditions are established. The preheating period is thereby increased. As shown in Fig. 5, the operation is very substantially improved by moving the thermostat farther from the elements, the temperature at first cut-out then being actually above the steady-state value by about 12 deg. F. (6·7 deg. C.). A small overshoot such as this has no harmful effect since the temperature falls immediately the oven door is opened to insert the food. A further point brought out by these two Figures is the reduction in differential obtained by placing the thermostat near the elements, the values obtained in the two cases being 10 deg. F. and 18 deg. F. (5·6 deg. C. and 10 deg. C.) respectively. From this point of view performance is better in the first position once steady

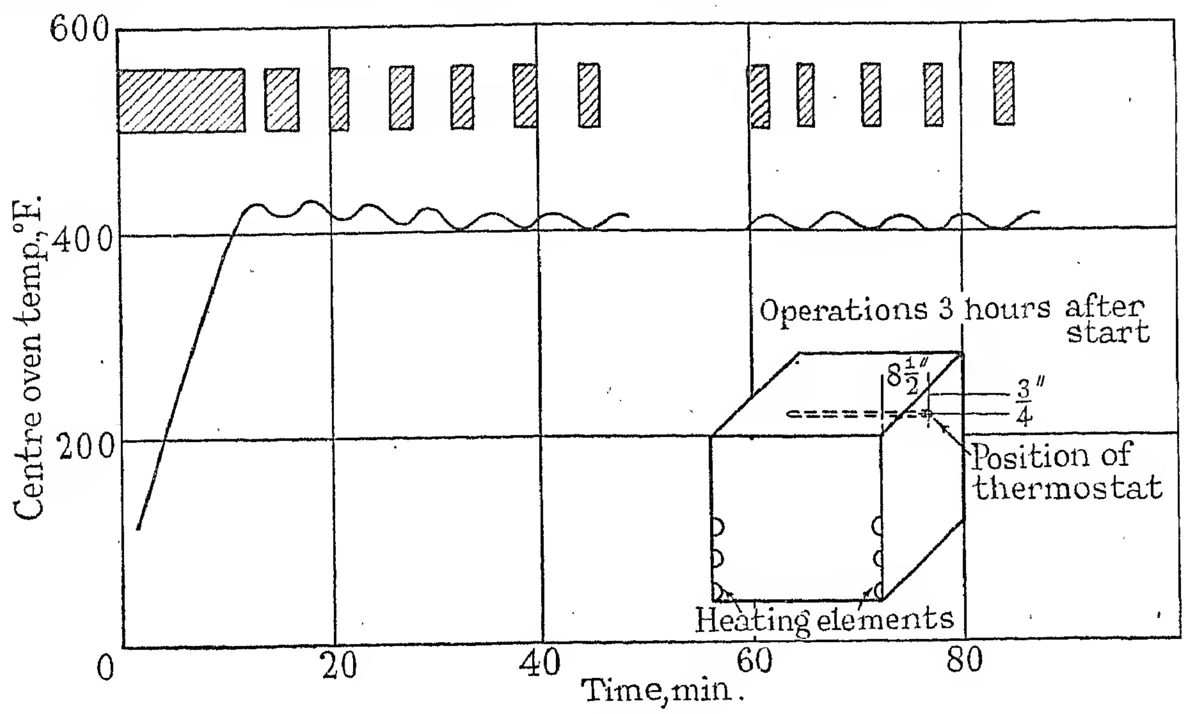

Fig. 5.—Effect of thermostat position on control of centre oven temperature: as Fig. 4, but with thermostat correctly placed.

Shaded portions indicate periods during which thermostat was closed.

conditions have been established, but in view of the effect on preheating time the arrangement is not admissible.

Precisely the reverse effect, obtained by placing the thermostat in a corner of the oven, very near the walls, where air circulation is restricted and the temperature rises more slowly than at the centre of the oven, is shown in Fig. 6. In this case the centre oven temperature at the first cut-out is some 60 deg. F. (33·3 deg. C.) above the steady-state value. The broken line shows the air

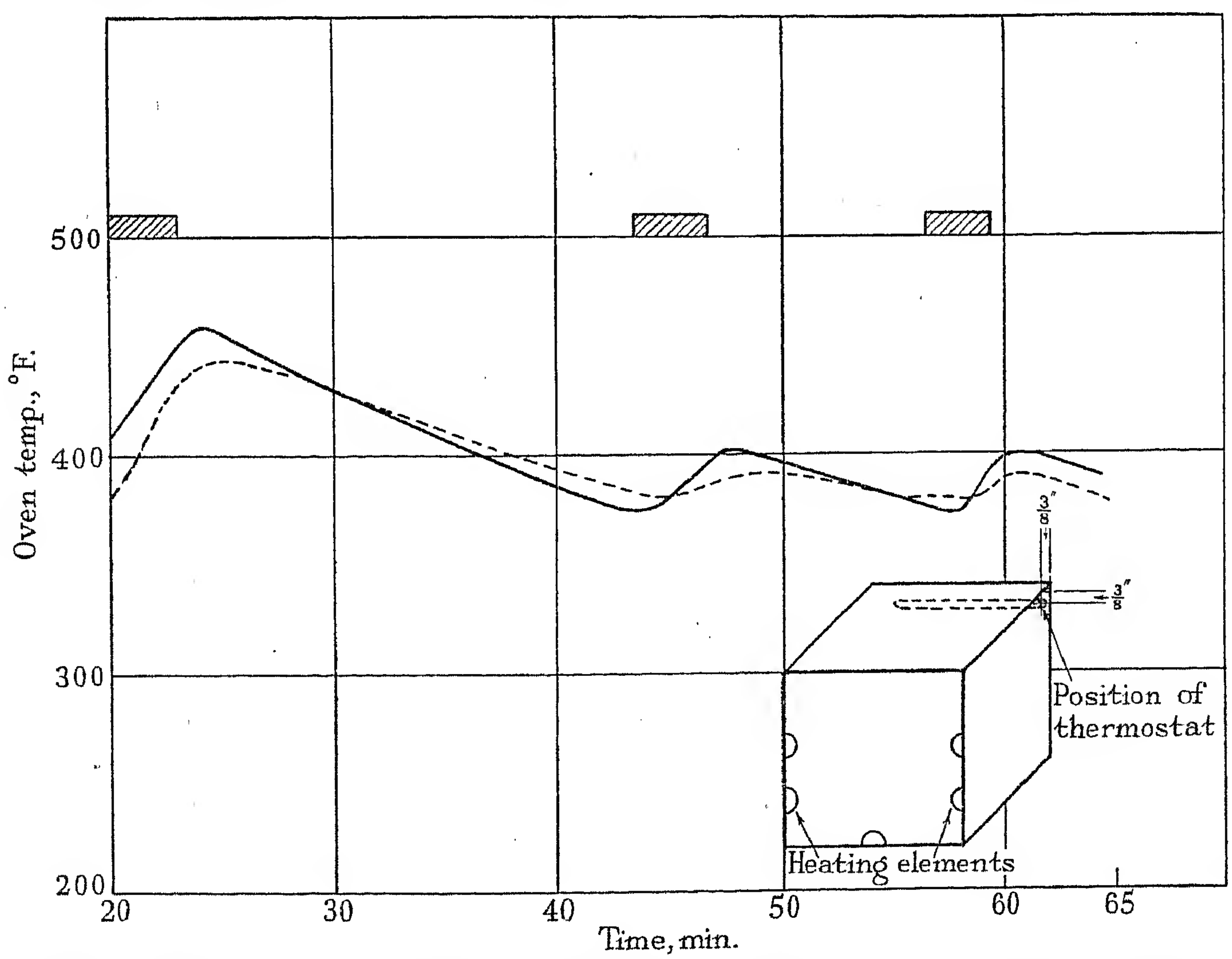

Fig. 6.—Effect of thermostat position on control of centre oven temperature: thermostat situated in region where free air circulation does not occur.

Shaded portions indicate periods during which thermostat was closed.

——— Centre of oven.
– – – – – Near oven thermostat.

temperature near the thermostat, and it will be seen that the temperature in this region continues to rise for more than a minute after that at the centre of the oven starts falling. It will also be seen that the differential at the centre of the oven is 26 deg. F. (14·4 deg. C.) as compared with 12 deg. F. in the neighbourhood of the thermostat. By moving the thermostat farther from the back wall, into a region of freer air circulation, the greatly improved, and entirely satisfactory, performance shown in Fig. 7 is obtained.

Effect of oven design on performance.

It has already been mentioned that in order to obtain a sufficiently short time cycle with present-day British cookers, very close control of air temperature is necessary. Provided the length of the cycle was not increased a much wider variation in temperature would, however, in no way detract from cooking performance. As such a change would simplify the design of the thermostat it is worth considering whether there are any means by which it could be brought about. Two possibilities suggest themselves, the first being to reduce to a minimum the heat capacity of those parts of the oven which undergo temperature-change, and the second to reduce the amount of lagging.

The latter expedient is the less desirable since it involves an increase in energy consumption, and therefore in the cost of cooking, whilst reducing heat capacity has no such effect. In the majority of ovens the parts whose heat capacities are most susceptible to reduction are the heating elements and the lagging material. The heat capacity of the latter could be almost entirely eliminated by the use of aluminium foil.

An alternative line of approach is to decrease the amount of radiant heating. The length of the time cycle then becomes of less importance, and if a system of entirely convective heating could be developed the time cycle should be of no importance whatsoever since the heating condition would depend only on oven air temperature. A slow rate of change might then be an advantage owing to the reduction in the effect of lag between the thermostat and air temperatures.

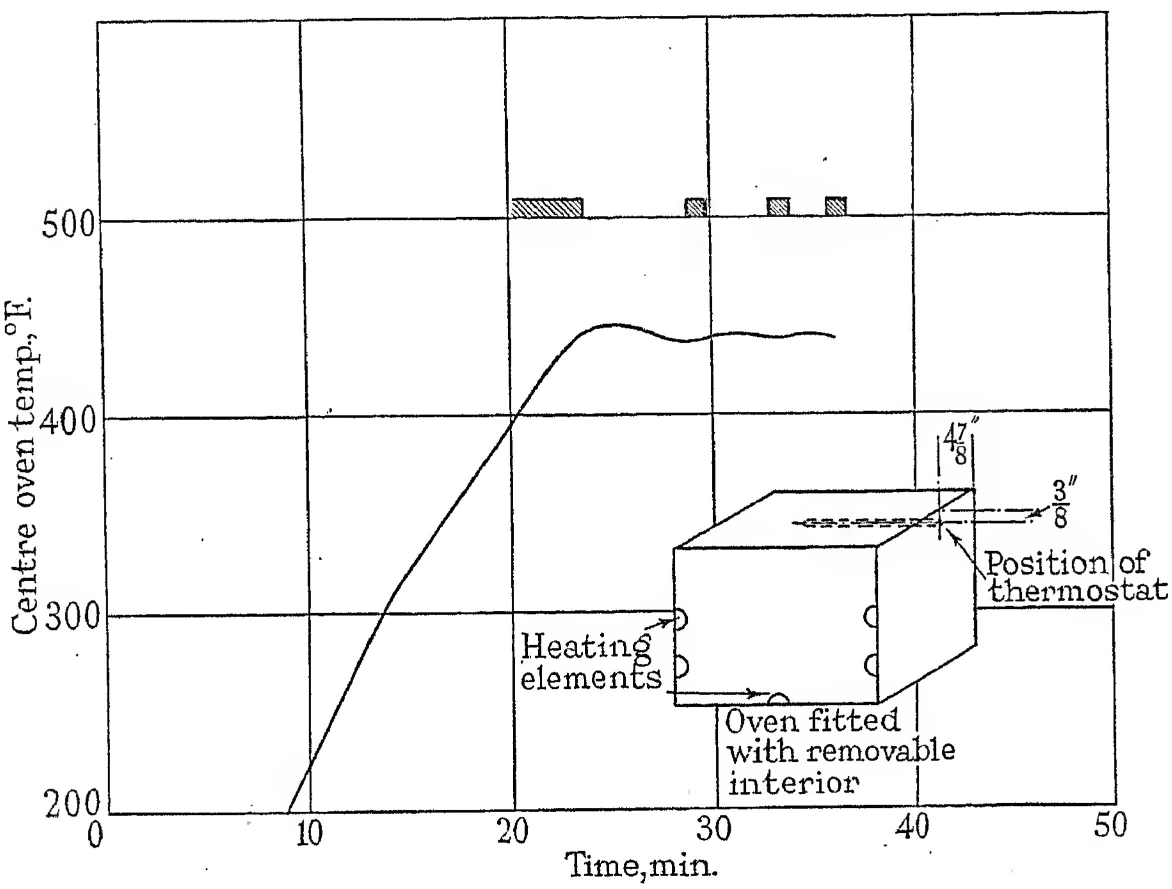

Fig. 7.—Effect of thermostat position on control of centre oven temperature: as Fig. 6, but with thermostat correctly placed.

Shaded portions indicate periods during which thermostat was closed.

GRILLERS AND GRILLER-BOILERS

The great majority of cookers sold in this country include in their hob equipment a fitment commonly known as a "griller-boiler" which is designed to serve the dual functions of griller and boiling-plate. A few models have a separate griller mounted below the hob, and in one or two instances the American practice of using the top element in a top-and-bottom-heated oven for grilling is followed.

In the most commonly employed form of griller-boiler, heating coils are mounted in porcelain formers, so designed that radiation in both the downward and upward directions is as little obstructed as possible, beneath a top plate of cast iron, or heat-resisting alloy steel. Very careful designing is necessary to ensure adequate strength for the formers. A wire guard protects the element, and a reflector is provided to concentrate the heat on to the metal top when grilling is not in progress.

The grilling performance of these units is in general very good, but their speed and efficiency as boiling-plates is low; they are not to be recommended for boiling unless grilling is carried out at the same time, in which

circumstances the overall "efficiency" is very high. Some manufacturers supply kettles of such a shape that they just cover the surface of the griller-boiler, and if these are used a considerably improved performance is obtained.

The relatively large area of the griller-boiler renders it very suitable for simmering a number of utensils simultaneously, and the low density of loading, as compared with that of most boiling-plates, is in this case an advantage.

A second type of griller-boiler, which is more frequently used as a separate unit than as a fitment in cookers, employs a sheathed-wire heating element and no top plate. It is provided with a reflector which can be placed above or below the element when the latter is used for boiling or grilling only. As a grill it is very satisfactory, and its speed and efficiency as a boiling-plate are greater than those of the open-coil metal-topped type. It cannot be used for grilling and boiling simultaneously, however, unless the kettle or saucepan is spaced away from the heating element, which naturally greatly reduces the speed of boiling, for with the vessel in contact with it the element does not reach a sufficiently high temperature for effective grilling. A further disadvantage is that if the contents of the vessel boil over, they are most likely to fall on to any food which is being grilled.

A possible criticism of griller-boilers in general is that the area which they offer for grilling is rather small, especially for the large cookers. Size is, to some extent, restricted by available hob space, and in that respect the separate griller offers the advantage that it can be designed to extend under the boiling-plates.

BOILING-PLATES

In no direction has improvement in cooker performance been more rapid than in the case of the boiling-plate. Yet, at least during the last 10 years, no revolutionary changes have been made in design. Progress has been due rather to the almost continual detailed improvement of well-established products.

Historical Review

During the latter part of last and the early part of the present century boiling-plate designers were very active, and it is very interesting to review their proposals in the light of our present-day knowledge.

In 1896 Chambers proposed the use of a resistor embedded in cement (consisting, according to his patent specification, of 2 parts by weight of plaster of paris and 1 part by weight of oxide of iron) in a dished metal top plate. In the following year Schindler and Jenny protected a form of construction in which the resistor was embedded in refractory around which a shell of aluminium, copper, or bronze was cast. At about the same time Archer embedded a crimped resistor in an enamel coating on the inside of a dished metal top, and many boiling-plates of this type were sold.

Of quite a different type were the Prometheus elements which were in commercial production about 1905. Instead of a resistance wire these elements employed a conducting film, made by mixing gold and platinum powder with a suitable flux, painted on to strips of mica, which, with suitable mica insulation, were clamped to the under-sides of steel top plates.

The use of a grooved iron top was first referred to in a patent granted to Teuber in 1905. The heating coils were not embedded, but were secured in enamel-lined grooves by shellac.

The early boiling-plate designers were seriously handicapped by the absence of a really good heat-resisting alloy. Such materials as german silver and eureka had to be pressed into service, and consequently wire temperatures and loadings were very restricted. The development of nickel-chromium alloys had been proceeding concurrently with that of boiling-plates since 1896, when Placet had obtained a patent covering the addition of chromium to metals such as manganese, ferro-nickel, etc., for the purpose of increasing their electrical resistance. Marsh and others carried on the development, and between 1910 and 1913 nickel-chromium alloys gradually came into commercial use.

A considerably increased wire temperature then became possible, and enamel and other embedding materials which had been used hitherto were no longer satisfactory. Solid metal tops continued to be used, but they were heated by wound mica elements clamped to their under-sides.

The new alloys were not, at first, very reliable, but they were rapidly improved and after a few years operating temperatures higher than those for which mica was suitable, became possible. At the same time there arose a growing demand for a boiling-plate which would give some visible evidence of its heat-giving capabilities. The combination of these two factors led to the development of various forms of exposed-resistor boiling-plates. The first plates of this type were so prone to damage by spilled liquids that their life was very short. Improvements aimed at facilitating the escape of spilled liquids were introduced, but no form of construction was found which satisfactorily accomplished this so far as viscous liquids were concerned. Open-coil plates were also very subject to mechanical damage and introduced a somewhat serious risk of shock to users who endeavoured to remove a foreign body which had fallen on to the heating coils. In addition it was found that, although the glowing coils gave the appearance of speed, these boiling-plates were not very fast and their efficiency was low.

The popularity of the high-voltage open-coil plates began to wane about 1925, and very soon the reaction against them assumed such proportions that manufacturers had to fit their open-coil plates with sheet-metal covers until such time as new designs could be developed.

The efficiency of these makeshift plates was so low that, in spite of the increase in loading, they were slower than many of the earlier enclosed plates. These temporary expedients were followed, in the natural course of development, by enclosed boiling-plates in which the heating coils were mounted in refractory blocks designed to permit the maximum radiation from the coil to plain or grooved boiling-plate tops. One example of this form of construction is still available, but generally speaking it never became very popular, being superseded by the three types of embedded-resistor boiling-plate and the low-voltage exposed-resistor plate which are now in common use and are described below.

Present-day Boiling Plates

Embedded-resistor plates.

(i) *Cast-iron top*.—This type of boiling-plate, in which the heating coil is embedded in refractory cement in grooves in a cast-iron top, may be regarded as a modern adaptation of Teuber's form of construction. In its present form it was first developed in Switzerland, and was gradually introduced into this country during 1925 and 1926. Subsequently very large quantities were imported. Although very massive, and slow and inefficient as compared with modern products, these plates marked a real advance so far as performance, life, and durability were concerned. British manufacturers soon became interested. New methods of production were developed which enabled refractory cements having better insulating properties to be used, castings were lightened, loadings raised, and performance generally was gradually improved. The course of this progress can be followed from figures given in Table 1 for typical plates of this type.

Table 1

Cast-iron Boiling-Plates

Date	Diameter	Loading	Boiling time*	Efficiency	Insulation resistance†
	in.	watts	min.	per cent	ohms
1925	$8\frac{1}{2}$	1 200	20	38	
1929	8	1 600	12·6	49	3 000
1929	8	1 600	10·5	61	23 000
1932	8	1 800	9·4	60	9 000
1934	8	1 800	9·4	60	250 000
1935	8	2 250	8·0	56	60 000

* Three pints of water in flat-bottomed vessel, 85 deg. C. temperature-rise.
† At maximum temperature with no vessel.

(ii) *Sheathed wire*.—The earliest forms of heating element consisting of a coiled resistor embedded in refractory inside a metal tube were produced some 20 years ago in America. Alternative methods of production were developed later in Sweden, and still more recently in this country. The earlier methods have been continually improved to meet modern conditions, and this type of plate is now in regular production in this country by three or four distinct methods.

(iii) *Sheet metal*.—The third type, which also originated in America, employed at first a light dished top, of alloy steel, in which the resistor was embedded in cement. This construction was found to be prone to distortion. To overcome this drawback the top was first bonded to a metal back-plate by means of metal eyelets, and later divided into two separate, relatively narrow, rings. It is in the latter form that this boiling-plate is now available.

Exposed-resistor plates.

The only type of exposed-resistor boiling-plate commonly fitted to British cookers employs a short resistor of large cross-sectional area, which is supplied with energy at a voltage of about 10 volts from a transformer built into the cooker.

For the sake of brevity the above types will, in the remainder of the paper, be referred to as: (1) cast-iron embedded, (2) sheathed-wire, (3) sheet-metal embedded, (4) low-voltage exposed-resistor.

Factors Affecting Performance

The relative importance of the chief properties of a boiling-plate, namely life, speed of boiling, efficiency, and insulation resistance, is largely a matter of opinion, but most people would probably place them in the above order. It is most important, however, that a proper sense of proportion should be maintained and that unwarranted sacrifices of other properties should not be made in order to obtain exceptionally good performance from one particular point of view. The factors on which these properties depend will now be very briefly outlined.

A boiling-plate consists essentially of a resistor and mechanical component, which serves as a support for both the resistor and the vessel. For convenience, the two components will be referred to as the resistor and the support, but the latter component will, in the majority of cases, be a complex one.

Life.

The useful life of a boiling-plate is ended when it no longer gives satisfactory service to its user, whether the cause be the failure of the resistor or the fracture or serious distortion of the support.

What is commonly referred to as a " normal failure " of the resistor occurs as a result of oxidation, which leads to the development of a hot spot where fracture eventually occurs. The rate of oxidation depends on the composition, temperature, and diameter of the wire, the term " composition " being broadly intended to include the manufacturing process.

Resistance alloys have been markedly improved during recent years. The basic composition of nickel-chromium alloys is still 80 % Ni and 20 % Cr, but, in consequence of the addition of minute amounts of other substances and improvements in manufacturing technique, the life of the best alloys under test conditions approximating to those of normal use is now 6 or 7 times as long as it was 3 or 4 years ago. Alternatively, the same life can be obtained at a temperature at least 100 deg. C. higher than previously. Progress has also been made with the development of the aluminium-containing alloys, which are now comparable with the best commercial nickel-chromium alloys so far as resistance to oxidation is concerned.

Failure of the resistor may also result from chemical or electrolytic action between it and some part of the support, from contact with an earthed part of the support, or from fracturing of the joint with the heavy end leads.

Possible causes of failure of the support will be considered in connection with the individual types of boiling-plate.

Speed of boiling.

Speed of boiling is directly proportional to the product of efficiency and loading. Efficiency is considered below. The upper limit of loading may be determined by either the resistor or the support, according to the type of construction employed. In the cast-iron embedded plate, for example, the determining factor is casting temperature, whereas in the low-voltage exposed-resistor and

sheathed-wire plates it is wire temperature. As increasingly higher wire temperatures become permissible the limit for embedded plates may be set by the insulating properties of the embedding cement.

Efficiency.

The thermal efficiency of a boiling-plate is defined as the ratio of the heat absorbed by the liquid heated, to the heat equivalent of the energy dissipated in the boiling-plate, multiplied by 100. Most of the heat which is not usefully employed is either absorbed by the plate itself or radiated from its under-surface and edges. The actual efficiency obtained must obviously depend to a large extent on the type of vessel used. So far as the boiling-plate itself is concerned the important quantities are its heat capacity, its mean temperature at the conclusion of the boiling operation, and the temperature of its exposed surfaces.

Insulation resistance.

The least satisfactory aspect of most modern boiling-plates is their insulation resistance when hot. The controlling factors are the composition and temperature of the refractory in which the element is embedded. Fig. 8 indicates the very rapid decrease in the electrical resistance of refractory insulating materials with increasing temperature. Very great improvement has been effected by the use of the new materials. For example, the insulation resistance of 2 250-watt 8-in. diameter cast-iron embedded plates under steady-state conditions with no vessel may now be as high as 60 000 ohms, whereas less than 10 years ago values of 10 000 ohms, or even less, with a loading of only 1 600 watts, were common. No manufacturer is really satisfied with this advance, however, and research for materials having still better insulating properties is continuing.

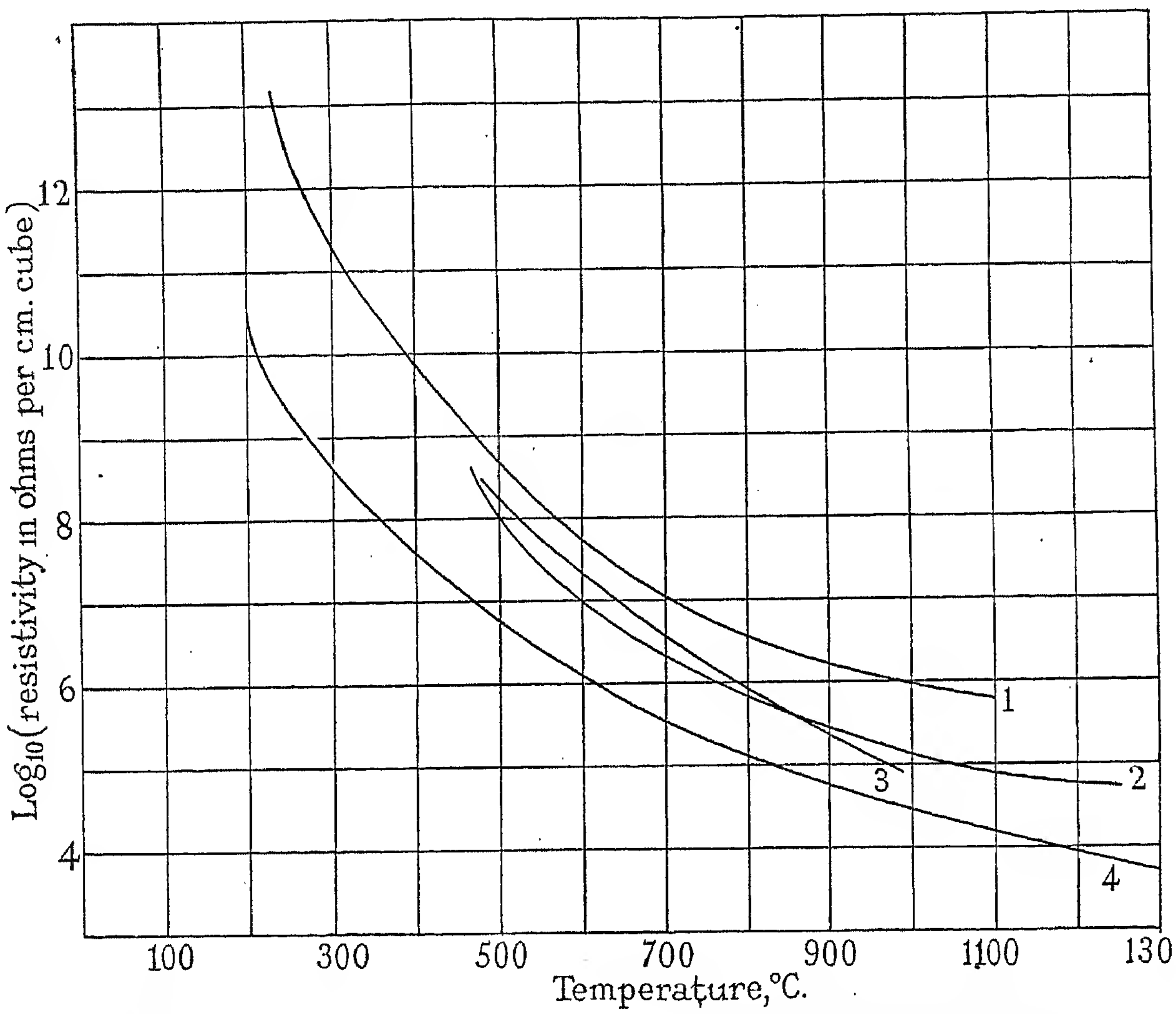

Fig. 8.—Variation of electrical resistivity of refractories with temperature.

1. Curve for fused silica, compiled from data given by A. Campbell (*Proceedings of the Physical Society*, 1913, vol. 25, p. 336) and by F. Horton (*Philosophical Magazine*, 1906, vol. 11, p. 505).
2. Magnesia (F. Horton: *Philosophical Magazine*, 1906, vol. 11, p. 505).
3. 90 % Zircon sand + 10 % Grosalmerode clay.
4. Silimanite.

Appraisal of Different Methods of Construction

Exposed-resistor method.

(i) *High-voltage type.*—This form of construction possesses the advantages of psychological appeal, very high insulation resistance, and low replacement cost, but these are more than offset by danger to the user, proneness of the resistor to injury, low efficiency, and the fact that the wire temperature for a given loading is higher than in the case of an embedded plate of similar dimensions. This latter disadvantage arises from the well-known fact that for a given energy dissipation the temperature-rise in a wire is less if the wire be lagged than if it be bare. This phenomenon can be readily demonstrated by placing in circuit a cast-iron boiling-plate, having the refractory completely removed from about 1 in. of the groove, and partially removed, in such a manner as just to expose the outside of the coil, from an adjacent part of the groove. When conditions become steady, it is obvious from visual inspection that the completely

exposed part of the coil is considerably hotter than the part which is embedded.

The wire temperature is still further increased during a boiling operation since the transmission of heat is almost entirely by radiation, and the surface of the vessel is at a higher temperature than the surroundings to which the element radiates when uncovered. If a vessel with a highly reflecting base is used the increase in temperature is very large.

(ii) *Low-voltage type.*—The low-voltage boiling-plate possesses all the advantages which are associated with the use of an exposed resistor, and at the same time is largely free from the disadvantages which are inherent in the high-voltage type. Danger of shock is entirely removed, the very robust resistor is not readily susceptible to damage, and on account of its large cross-sectional area it is able to withstand temperatures considerably in excess of those which are permissible with any other boiling-plate.

From the point of view of psychological appeal, and ability to create an impression of speed, the low-voltage plate is pre-eminent.

Its principal disadvantages are that its initial cost, including the transformer, is substantially higher than that of any other type of plate, and that, in common with all plates which depend mainly on radiation for heat transfer, its efficiency is low, especially when used with aluminium or other utensils having bright bases.

Cast-iron embedded method.

Apart from the general advantages associated with the embedded construction, the chief merit of the cast-iron type is that the resistor is so definitely located along its whole length that the clearance between adjacent turns can be very small, and in consequence a very long coil, of large-diameter wire, can be accommodated. In an 8-in. diameter boiling-plate, for example, each coil may be as long as 60 in. Consequently the wire temperature is exceptionally low: in an 8-in. diameter 2 250-watt plate it may be as low as 800° C. under steady-state conditions with no vessel, and, so far as oxidation of the resistor is concerned, life is practically unlimited.

Under normal-use conditions the wire temperature is still lower since the heat transfer to the vessel is mainly by conduction, either directly from metal to metal, or through the small air-gap between the boiling-plate and the vessel. The actual temperature depends on the width of this gap. The relation between mean wire temperature and gap for an 1 800-watt boiling-plate is shown in Fig. 9. With a commercial machined-bottom aluminium or cast-iron vessel, the mean gap is of the order of 0·005 in., and the wire temperature is approximately 270 deg. C. lower than when no vessel is in use. The temperature of the casting depends in a similar way on the flatness of the bottom of the cooking utensil. It will be seen from Fig. 10 that with a machined-bottom vessel the maximum casting temperature is only 250° C., and with any good-quality commercial vessel it is lower than when the surface of the boiling-plate is uncovered. With so low a temperature-rise the losses by absorption in, and radiation from, the boiling-plate are low, and its efficiency is therefore high in spite of its relatively large heat-capacity.

Under life-test conditions* no cracking or serious distortion occurs provided good-quality properly-annealed castings are used, and it follows that no such trouble is to be anticipated in normal use with good-quality commercial utensils. If badly-distorted pans are used, however, the casting may reach a temperature considerably higher than that obtained with no vessel, and cracking may then occur after quite a short period of use.

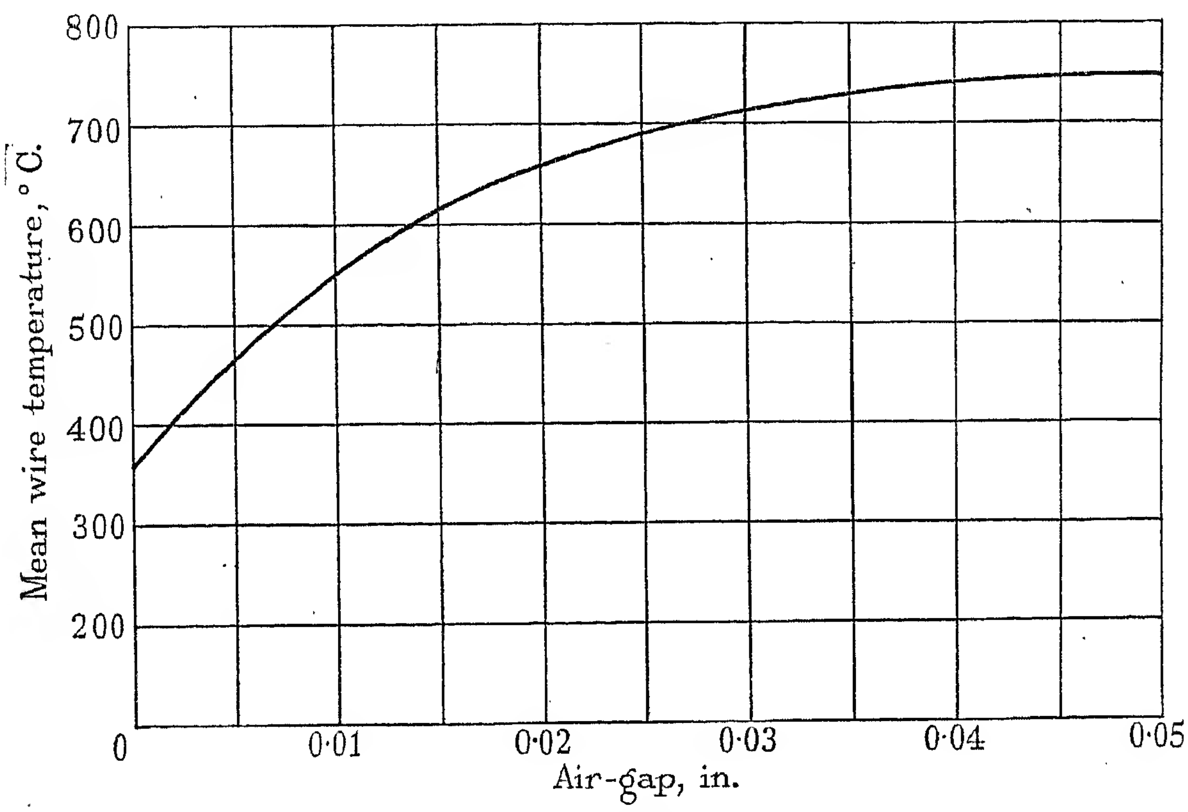

Fig. 9.—Relation between air-gap and mean wire temperature for 8-in. cast-iron boiling-plate; loading 1 800 watts.

* See British Standard Specification No. 744—1937.

In some parts of the Continent the use of any but machined-bottomed utensils with cast-iron boiling-plates is practically unknown, and is regarded as abuse. While

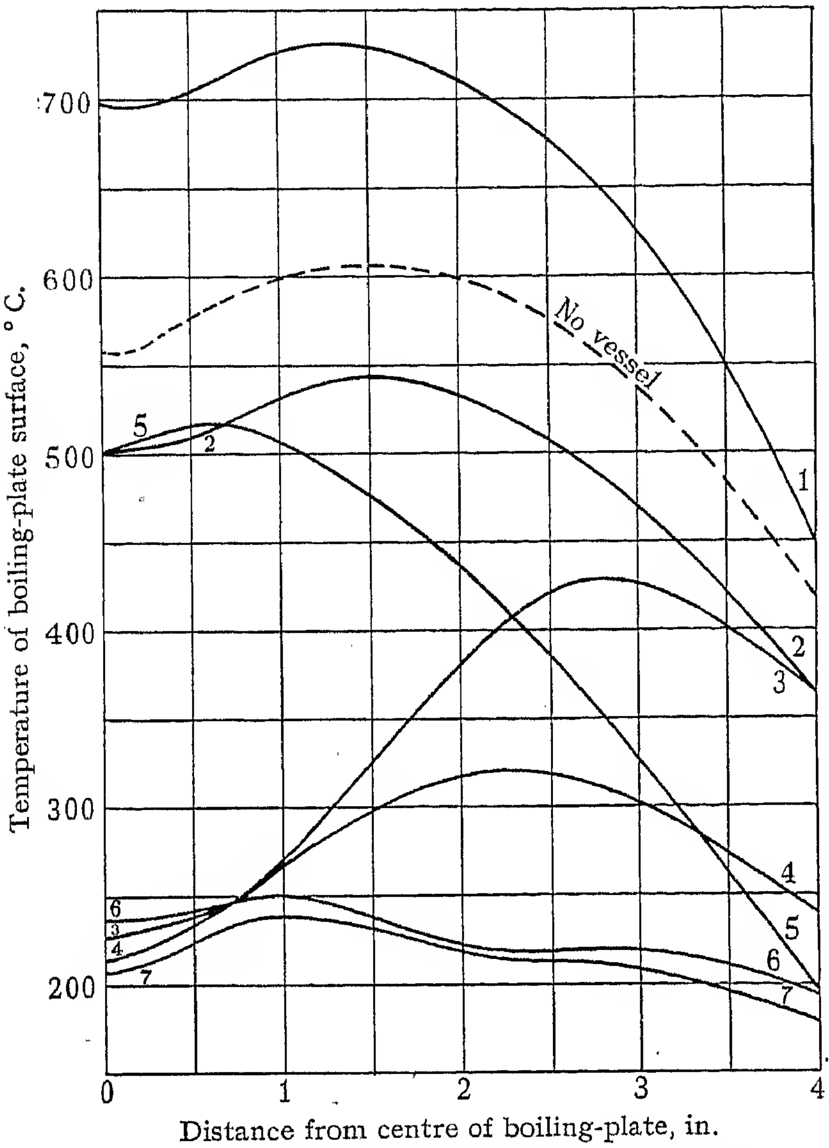

Fig. 10.—Variation of casting temperature with different vessels using 8-in. diameter boiling-plate; loading 1 800 watts.

1. Kettle with re-entrant bottom.
2. Enamelled iron pan.
3. Pressed aluminium pan with convex bottom.
4. Ordinary kettle with copper bottom.
5. Pressed aluminium pan with concave bottom.
6. and 7. Aluminium pans with machined bottoms.

it is by no means necessary to go as far as this in order to eliminate all risk of cracking, such a course is well justified on the grounds of the resulting improvement in performance and economy of operation.

A discussion of the causes of, and possible methods of eliminating, cracking under severe conditions of use scarcely falls within the scope of the present paper. It may be mentioned, however, that the trouble is frequently aggravated rather than alleviated by the use of heat-resisting-alloy irons, which, on account of their relatively large coefficients of expansion and low thermal conductivities, are subjected to greater stresses in use than arise with straightforward iron castings.

Failure of the resistor may occur through liquids spilled on the top of the plate creeping up the inside of the rim and soaking the refractory. Serious creepage only occurs when the boiling-plate is cold. If the surface of the plate is kept dry, and in particular care is taken not to use an excessive quantity of water for cleaning purposes, no trouble should arise. With a view to eliminating this cause of failure one manufacturer provides a double drip rim in the manner shown in Fig. 11.

Corrosion of castings, which in many areas is seldom heard of, but in others is quite serious, is also mainly dependent on conditions of use. Provided the surface of the boiling-plate is kept clean and dry at all times, no corrosion should occur.

Sheet-metal embedded method.

Provided a suitable material is chosen for the top, this construction is free from the troubles due to cracking and corrosion to which the casting of the cast-iron embedded plate is prone under severe conditions of use. This advantage is gained, however, at the expense of some increase in wire temperature; firstly, because the construction does not permit of the accommodation of so great a length of wire, secondly owing to the absence of the thermally-conducting fins between the turns of the resistor, and thirdly owing to the difficulty of obtaining a really effective and permanent bond between refractory cements and sheet metal. With the continued improvement in resistance wires, this disadvantage becomes less serious.

The substitution of sheet metal for cast iron results in a substantial reduction in heat capacity.

Sheathed-wire method.

The main appeal of the sheathed-wire boiling-plate is psychological, and from this point of view it is the nearest mains-voltage equivalent to the low-voltage exposed-resistor plate. Its surface temperature is of necessity very much lower, about 700° C. being a maximum figure, and consequently the density of loading is also lower. Its efficiency, on the other hand, is much

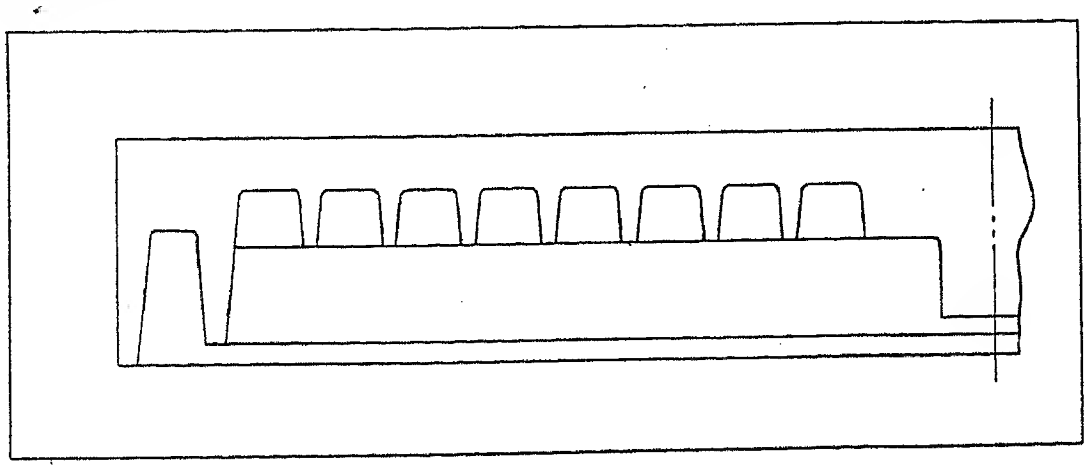

Fig. 11.—Double drip rim casting.

higher since the vessel, being in contact with the sheath, receives a considerable amount of heat by direct conduction.

So far as wire temperature and life are concerned, comparison must be made with other types of embedded boiling-plates. When designing the cast-iron and sheet-metal embedded plates, everything possible is done to keep the temperatures of both the top and the wire as low as possible. This cannot be done with the sheathed-wire plate since its surface must operate at red heat if its greatest advantage is to be retained. All that is possible, therefore, is to keep the temperature-difference between the resistor and the sheath as low as possible by the use of the largest-diameter coil that can be accommodated. With present-day resistance wires a thoroughly satisfactory life can be obtained, but wire temperature is very definitely the limiting factor and considerable care in design is still required.

Tubes of nickel, calorized steel, stainless steel, and nickel-chromium, have been used from time to time for the sheath. The last-named, which has only recently become available in solid-drawn form, offers complete freedom from oxidation, cracking, and corrosion. Its cost, for a given size of plate, is several times that of a casting, and this form of construction is therefore inherently much more expensive than that used in the cast-iron embedded plate.

The problem of liquid creepage arises only at the ends of the elements, and these can be protected either by sealing the ends of the tubes, for which purpose glass is sometimes used, or by shrouding them.

Owing to the high operating temperature the insulation resistance of sheathed-wire plates is considerably lower than that of other embedded types. A typical figure for an 1 800-watt 8-in. diameter plate at maximum temperature with its surface uncovered, is 40 000 ohms. The corresponding figure for a cast-iron boiling-plate of similar size and loading, employing the same refractory, is about 250 000 ohms. The operating temperature is further increased, and the insulation resistance correspondingly lowered, by the use of vessels having markedly curved or distorted bases, especially if their surfaces are highly reflecting. In extreme cases, such as would lead to rapid cracking of cast-iron plates, breakdown of the insulation may occur.

Table 2

EFFECT OF CURVATURE AND FINISH OF BASE OF VESSELS ON BOILING TIME, FOR VARIOUS TYPES OF BOILING-PLATE

Boiling-plate		Boiling times for 3 pints of water, using vessels as stated					
		Thin aluminium			Heavy (machined bottom) aluminium		Vitreous-enamelled iron
Type	Loading	Vessel A	Vessel B	Vessel C	Vessel D	Vessel E	Vessel F
	watts	min.	min.	min.	min.	min.	min.
Cast-iron embedded	1 800	10·3	11·7	13·9	9·4	9·4	14·2
Sheathed wire	1 500	12·8	12·2	12·7	11·7	11·6	11·1
Low-voltage exposed-resistor..	2 250	15·9	14·9	15·1	14·2	12·0	11·5

Vessels

Some reference has already been made to the effect of the type of cooking utensil on performance, but this question is felt to be of sufficient importance to warrant a few further words.

Table 3

Vessel	Type	Base	Maximum distance between base of vessel and boiling-plate
			in.
A	Thin pressed aluminium	Concave	$\frac{1}{50}$
B	do.	Convex (irregular)	$\frac{1}{20}$
C	do.	Convex (regular)	$\frac{1}{20}$
D	Heavy aluminium	Machined flat	—
E	do.	Painted black	—
F	Vitreous-enamelled iron	Concave	$\frac{1}{16}$

Table 2 gives boiling times obtained with 6 commercial vessels on each of 3 boiling-plates of different types. The tests were conducted some years ago, and the loadings are in some cases below present-day values.

The vessels used are described in Table 3. All boiling times given are for 3 pints of water, and the conditions of test were as laid down in Technical Report Ref. Z/S1 of

the British Electrical and Allied Industries Research Association.*

Cast-iron embedded, sheathed-wire, and low-voltage exposed-resistor plates, were tested. Examination of the test results shows that the performance of both the cast-iron embedded and the low-voltage exposed-resistor plates is largely affected by the type of vessel used, although in quite different ways. With the cast-iron plate, the shortest boiling time is obtained with the flat-bottomed vessel. The absorption coefficient of the base has no effect, as is shown by comparison of the results obtained with Vessels D and E, and the boiling time increases with curvature of the vessel, the longest time being obtained with the vitreous-enamelled utensil. The performance of the low-voltage exposed-resistor plate, on the other hand, is very little affected by the curvature of the vessel bottom, but varies considerably with its absorption coefficient; blackening the bottom of Vessel D effects a saving of as much as 2·2 minutes. The shortest time is obtained with the vitreous-enamelled vessel, and the longest with the concave aluminium utensil. The sheathed-wire plate, owing to its ability to adjust the method of heat-transfer to suit prevailing conditions, is much less affected by variation in vessels. With this type of plate also the shortest time is obtained with the vitreous-enamelled vessel, which shows that absorption coefficient is more important than flatness.

Simmering with Embedded Boiling-Plates

Prior to the introduction of 8-in. diameter cast-iron boiling-plates loaded to 2 250 watts, embedded plates were invariably provided with two coils and controlled by 3-heat series-parallel switches. With coils of equal resistance this enabled full, half, or quarter loadings to be obtained. With a full loading of 1 600 watts the quarter loading was on the high side for simmering. Increasing the full loading to 1 800 watts accentuated the difficulty, and when it was raised to 2 250 watts some means of providing a lower loading than 562 watts became essential. Two methods have been adopted. The first is to provide an external resistance which can be connected in series with the boiling-plate elements to give an additional extra-low loading. The second is to employ three coils of equal resistance in the boiling-plate itself, and to control them in such a way that one coil can be used alone, two or three coils can be connected in parallel, or the three can be employed in series. Either arrangement requires a special 5-position switch, and the following loadings are available: Two-coil plate with external resistance, 2 250 watts, 1 125 watts, 562 watts, 250 watts; 3-coil plate, 2 250 watts, 1 500 watts, 750 watts, 250 watts. The first arrangement has the advantages that the third (normal "low") loading of 562 watts is more convenient and economical in use than the corresponding loading of 750 watts obtained with the 3-coil plates, and that standard plates are used. The latter advantage appears to the author to be of very real value since it greatly simplifies replacement and the substitution of 4-heat plates for 3-heat plates on existing cookers. The second arrangement has the advantages that no external resistance has to be provided and that no energy is wasted in such a resistance when the lowest loading is employed.

The external resistance gives a free choice of the value of the minimum loading, while with the 3-coil plate this is determined by the resistances of the coils.

As to the precise meaning of the term "simmering," there appears to be some difference of opinion. There is no doubt, however, that for certain cooking operations it is very desirable to be able to maintain a temperature between 180° F. and 190° F. (82·2° C. and 87·7° C.) for long periods and that for other purposes an energy input slightly higher than that required just to maintain boiling is necessary. There also appear to be certain other operations for which a temperature between 200° F. and 210° F. (93·3° C. and 98·8° C.) is ideal.

Clearly no one loading can allow all these requirements to be met with the same area of contact between vessel and boiling-plate, especially with the additional complications of tolerances on loadings and supply voltage and variations between vessels. Provided, however, that the loading is not seriously excessive the rate of heat-transfer can be very critically adjusted by varying the area of contact. So far as the value adopted for the extra-low loading is concerned it is difficult to determine the best compromise by laboratory experiments, and experience will have to be taken as the final criterion. The limited experience so far available appears to indicate that a loading somewhat lower than the present 250 watts might be more generally useful.

ACKNOWLEDGMENTS

The author desires to tender his thanks to the Rheostatic Co., Ltd., for kindly placing at his disposal the curves from which those reproduced in Figs. 4–7 were selected, relating to the thermostatic control of ovens; also to Messrs. Belling and Co., Ltd.; British National Electrics, Ltd.; Elexcel, Ltd.; Falk, Stadelmann and Co., Ltd.; Falkirk Iron Co., Ltd.; Hotpoint Electric Appliances Co., Ltd.; Jackson Electric Stove Co., Ltd.; Moffat, Ltd.; Siemens Electric Lamps and Supplies, Ltd.; and Simplex Electric Co., Ltd.; for supplying information concerning their current products.

* This report was used as the basis for British Standard Specification No. 744—1937.

[The discussion on this paper will be found on page 595.]

ELECTRIC COOKERS FOR DOMESTIC PURPOSES, WITH SPECIAL REFERENCE TO MAINTENANCE COSTS

By J. N. WAITE, Member.

[*Paper first received* 21*st June, and in final form* 21*st July,* 1937; *read before* THE INSTITUTION 20*th January, before the* SOUTH MIDLAND CENTRE 24*th January, before the* NORTH-EASTERN CENTRE 14*th February, before the* NORTH MIDLAND CENTRE 15*th February, before the* NORTH-WESTERN CENTRE 1*st March, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 7*th March, and before the* WESTERN CENTRE 28*th March,* 1938.]

SUMMARY

It is proposed to examine the economic aspect of electricity supply for domestic purposes, in which the electric cooker appears to offer the largest market for any individual piece of apparatus; to give reasons for the belief that the electric cooker offers the largest market for electricity supply in the domestic field; to offer suggestions on ways and means of developing this market; and to give detailed information on the maintenance cost of domestic electric cookers.

CONTENTS

THE ECONOMIC ASPECT OF DOMESTIC SUPPLY

In considering the economic aspect of domestic supply, the result that matters is the overall effect of the use of all the various forms of domestic current-consuming apparatus. If the overall result is satisfactory, the effect of individual pieces of apparatus need not be studied. It will be obvious that, generally speaking, the more numerous the forms of apparatus used, the more the diversity of use and the higher will be the resultant load factor.

If the conditions obtaining in domestic premises are considered, it will be apparent that the general habits of householders are bound to produce a large diversity in the use of current-consuming apparatus, and it may be expected that while the load factor of a well-equipped individual house may be low, yet the resultant combined load factor of a large number of such houses may be relatively very high. This reasoning is borne out by actual results, as shown in Table 1, which gives statistics for a working-class housing estate of 500 houses over a period of 3 years. It will be noted that the load factors of the individual houses, based on the actual maximum demand of the individual houses, range from 1·9 % to 2·4 %, but the load factors of the estate of 500 houses, based on the combined maximum demand of the estate at the time of the maximum load of the undertaking, range from 46 % to 56 % for the 3 years, showing a very high order of diversity.

In the summer months the maximum load on the estate occurs at about 11.30 a.m. As the undertaking's peak occurs in the month of December between 4 p.m. and 5.30 p.m., it will be appreciated that the value of the local morning peak can be disregarded so far as generation and main transmission standing-charges are concerned. The only fixed costs affected by this morning

Table 1

WORKING-CLASS HOUSING ESTATE OF 500 HOUSES, EACH EQUIPPED WITH ONE MULTI-PURPOSE COAL FIRE, SEVEN LIGHTING POINTS, SMALL ELECTRIC COOKER (5 KW), ELECTRIC WASH-BOILER (3·2 KW), AND ONE PLUG POINT; RATING ASSESSMENT, £13 PER HOUSE (AVERAGE)

Year ending 31st March	1934	1935	1936	Average
Maximum load of each consumer (kW)	5	5	5	5
Maximum load (kW) from estate:—				
Total	343	310	325	326
Average per consumer	0·686	0·62	0·65	0·65
Maximum load (kW) from estate at time of undertaking maximum load:—				
Total	109	105	98	104
Average per consumer	0·219	0·21	0·196	0·21
Average consumption per consumer per annum (units)	1 060	848	837	915
Average load factor of individual consumer (%)	2·4	1·9	1·9	2·09
Load factor of estate on local peak (%)	17·6	15·6	14·7	16·02
Load factor of estate on load at undertaking maximum load (%)	55·7	46·1	48·7	50·22

peak are those for local distribution. It is therefore legitimate to compute the cost of giving the supply on the basis of the whole of the capital cost of the local distribution, plus an allocation for fixed charges for generation and main transmission proportionate to the demand at the time of the undertaking peak, plus the running cost of the units supplied. Such a computation is given in Table 2, together with the income; the figures are based on the costs of the author's undertaking (Hull). It will be seen that, with a normal domestic tariff of 15 % of the rateable value and ½d. per unit, domestic supply is an economic proposition even with this type of house.

The housing estate from which these results are obtained is one of the Sutton Trust Estates, which are tenanted by the poorest of non-skilled manual workers, whose purchasing power is of a very low order. A multi-purpose coal fire is provided, and the consumptions recorded show that cooking is done on the fire during the winter and on the electric cooker during the summer months. Much higher consumptions are obtained from similar types of houses tenanted by the skilled artisan class, whose purchasing power is higher, with, of course, an increase in the individual load factor and in the combined load factor.

The records from this estate revealed an interesting point in connection with electric wash-boilers: the Monday morning peak was certainly the highest load of the week, but it was very little higher than that of any other day. We may deduce from this that the dangers of an abnormal demand due to consumers all using their cookers and wash-boilers at the same time on one day is very remote, and that householders do not all do their clothes-washing on the same day and at the same time. Further evidence that domestic apparatus does produce a high order of diversity and a relatively high load factor is provided indirectly by the results for the Hull undertaking given in Table 3. It will be noted that a great increase has taken place in domestic electrification, and, coincident with this expansion, the load factor of the undertaking has risen steadily over a period of 8 years from 34·6 % to 43·0 %.

Table 2

Actual cost of local distribution, £9 766; capital charge on local distribution, £708; fixed charge per kW for generation £3 1s. 5d., for transmission 8s. 8d., for other expenses £2 12s. 11d.; running charges, 0·1748d. per unit (demand and units figures taken from average in Table 1)

Income	£	Expenditure	£
Standing charge of 15 % on £12 or £13 each for 500 houses—£6 240	936	Capital charges on local distribution	708
Unit charge:— 457 500 at ½d. per unit	953	Generation fixed charge (104 kW plus 5 %) = 109·2 kW at £3 1s. 5d. per kW	335
		Transmission fixed charge (104 kW plus 5 %) = 109·2 kW at 8s. 8d. per kW	47
		Other fixed charges (104 kW plus 5 %) = 109·2 kW at £2 12s. 11d. per kW	289
		Unit charge (457 500 units at 0·1748d. per unit)	333
	£1 889		£1 712

Table 3

Year ended 31st March	Total meter connections	Units sold on 2-part tariff, as percentage of total		Cookers connected	Kettles connected	Wash-boilers connected	Load factor of undertaking
		Domestic only	Domestic and commercial heating and cooking				per cent
1929	23 634	4·91	—	—	—	10	34·63
1930	31 574	5·28		239	156	50	35·79
1931	39 785	8·59		2 174	1 931	100	36·11
1932	48 759	13·08	13·24	4 938	4 443	470	36·93
1933	57 841	17·27	17·94	6 592	6 029	791	39·37
1934	66 726	18·85	20·01	7 406	6 875	1 113	38·75
1935	75 115	19·48	20·89	8 673	8 166	1 677	41·34
1936	82 891	22·17	24·03	12 010	11 545	2 980	41·32
1937	91 038	24·17	27·23	15 538	15 022	4 956	43·00

Table 4 gives the sales, classified under various headings, over the same period. While all classes of supplies have increased, when the various classes are expressed as a percentage of the total the only class showing an increase is the units sold under the domestic tariff; so that the increase in load factor cannot be ascribed to an abnormal increase in long-hour power units. A number

Table 4

UNITS SOLD, IN MILLIONS (EXCLUDING PUBLIC LIGHTING)

Year	Total		Lighting						2-part tariff						Large-power special agreements			Small-power tariffs		
			Flat rate			Brighton tariff			Domestic			Domestic and commercial heating and cooking								
	Number	Average price	Number	Percentage	Average price	Number	Percentage	Average price	Number	Percentage	Average price	Number	Percentage	Average price	Number	Percentage	Average price	Number	Percentage	Average price
		d.			d.			d.			d.			d.			d.			d.
1922	29·6	2·43	2·7	9·22	7·76	0·7	2·35	6·04							21·2	71·66	1·47	5·0	16·77	3·08
1923	38·9	1·91	3·2	8·14	7·53	0·8	2·07	5·33							29·7	76·47	0·95	5·2	13·32	3·49
1924	46·2	1·48	3·5	7·50	6·09	0·9	2·05	3·95	0·2	0·41	2·63				35·9	77·79	0·84	5·7	12·25	2·26
1925	53·2	1·36	4·2	7·89	4·95	1·1	2·11	3·26	0·7	1·30	2·25				41·5	78·07	0·84	5·7	10·63	2·02
1926	60·4	1·30	4·6	7·65	4·92	1·4	2·34	3·25	1·4	2·34	2·16				45·9	75·96	0·78	7·1	11·71	1·74
1927	61·4	1·57	4·5	7·33	4·97	1·6	2·60	3·32	2·4	3·87	1·97				45·7	74·52	1·05	7·2	11·68	1·90
1928	70·1	1·25	5·1	7·31	4·97	1·9	2·77	3·20	2·9	4·19	2·06				52·2	74·43	0·73	7·9	11·30	1·52
1929	74·4	1·12	5·2	7·01	4·39	2·2	2·95	2·85	3·7	4·91	1·84				55·4	74·46	0·65	7·9	10·67	1·42
1930	84·4	1·12	6·1	7·25	4·41	2·7	3·17	2·73	4·5	5·28	1·75				62·6	74·19	0·64	8·5	10·11	1·40
1931	100·9	1·11	7·2	7·18	4·36	3·1	3·05	2·70	8·7	8·59	1·30				72·1	71·50	0·64	9·8	9·68	1·45
1932	111·9	1·02	6·8	6·06	4·32	3·7	3·32	2·62	14·6	13·08	1·16	14·8	13·24	1·16	77·4	69·15	0·62	9·2	8·23	1·13
1933	119·7	1·01	6·6	5·54	4·43	4·3	3·60	2·54	20·7	17·27	1·09	21·5	17·94	1·07	78·0	65·16	0·58	9·3	7·76	1·27
1934	129·9	1·01	6·5	5·00	4·47	4·8	3·70	2·63	24·5	18·85	1·09	26·0	20·01	1·06	82·5	63·51	0·60	10·1	7·78	1·26
1935	148·6	0·972	6·5	4·41	4·428	5·6	3·74	2·643	28·9	19·48	1·07	31·0	20·89	1·031	94·8	63·77	0·589	10·7	7·19	1·205
1936	170·6	0·905	6·4	3·75	4·138	5·9	3·46	2·631	37·8	22·17	0·97	41·0	24·03	0·93	106·3	62·31	0·572	11·0	6·45	1·21
1937	193·3	0·894	6·6	3·42	4·154	6·6	3·40	2·54	46·7	24·17	0·934	52·6	27·23	0·88	117·2	60·63	0·597	10·3	5·31	1·20

of factors have contributed to the increase in load factor, and it appears reasonable to assume that the increase in domestic units is one of the material factors. As the load factor accruing from large-scale domestic electrification is of a much higher order than is usually supposed, relatively low tariffs for domestic supply are fully justified.

The case already considered is that of an undertaking where the winter afternoon peak is higher than the morning load at any time. In this case it is possible to utilize the diversity between domestic demands and other demands with economic advantage to the undertaking and to the consumer, without any misgivings or fears. In undertakings serving purely residential areas and having very little industrial power load, the margin between the morning and afternoon demands will be less relatively, and the development of the domestic load will rapidly absorb that margin, bringing about a change in the characteristic of the load curve, with the undertaking maximum load occurring in the morning. This has already occurred in some undertakings, and is rapidly being approached in others. Those in control of such undertakings are somewhat apprehensive of the financial effect of further development of domestic load, with the existing tariffs.

The advent of the national grid has not altered the fundamental economics of the problem. With "independent generation," the standing charges for generation are governed entirely by the maximum demand, irrespective of the time when the maximum demand occurs. Therefore, if domestic electrification—or, for that matter, any load development—was an economic possibility with independent generation, it is equally so with supplies from the grid on the grid tariff. In fact, the present position must be somewhat the better, for it must be presumed that the undertaking is taking the grid tariff because the costs under this are lower than they would have been with independent generation.

While there has been no change in the fundamental economics, there has been a change in the incidence of certain factors. With independent generation, as soon as a generation extension is completed, the full capital charges accrue and have to be met. Full load is not immediately available for the plant, and therefore the capital charge per unit will increase. As load is provided for the new plant, the capital cost per unit falls until another generation extension is required, when another sudden increase in capital charge per unit will occur. Thus, under independent operation, the capital charge per unit for generation goes through cycles of sudden increase and progressive decrease. The same kind of cycle occurs on the distribution side, but the incidence is not so often noticed because, usually, there are a large number of distribution extensions progressing, each one of which is in a different part of its cycle, thus tending to cancel out the effect. The grid tariff averages out the cycle, and obviously any comparison between independent-generation and grid-tariff conditions must be based on the average of the cycle of generation costs.

The author has heard it argued that because with independent generation spare-plant capacity existed, new load could be connected up without increasing the undertaking's standing costs for generation, whereas,

with the grid tariff, additional load means that the undertaking's costs will be increased, and thus the undertaking is worse off under the grid tariff. This argument is entirely fallacious for, under independent generation, if spare plant exists the capital charges on this are already being incurred and met, while under the grid tariff such charges are not made until the actual demand occurs.

The opinion is sometimes advanced that an undertaking cannot afford to develop the domestic load beyond the point where the morning peak equals the winter afternoon peak, as, beyond this, all new demand would have to be paid for at the full grid-tariff standing charge. An engineer advancing this opinion would have no difficulty in showing that if all new business had to bear the full standing charge for bulk supply, the normal tariffs for domestic supply would be uneconomic, but in so doing it would have to be assumed that no diversity existed between the new domestic-supply demand at peak hours and other demands on the undertaking. This assumption would obviously be incorrect. Quite a small value of diversity would be sufficient to ensure that the normal tariffs for domestic supply would bring in an economic return. As an illustration, assume the following: (*a*) A load factor of 40 % for domestic supply. (*b*) A diversity value of 1·6 between domestic-supply and other demands. (*c*) A bulk-supply tariff of £3 10s. per kW of maximum demand plus 0·225d. per unit. (*d*) Transmission and distribution charge, £6 per kW. (*e*) Domestic tariff of 15 % of rateable value plus ½d. per unit, and a house of £15 rateable value. (*f*) Annual consumption of 3 504 units.

The *cost of giving a supply, per kW of maximum demand*, would then be as follows:—

£9 10s. ÷ 1·6	=	1 425d.
3 504 units at 0·225d. + 10 % for loss ..	=	867d.
Total		2 292d.

The *income* accruing would be:—

15 % of £15	=	540d.
3 504 units at ½d.	=	1 752d.
Total		2 292d.

These values are close enough to practical values to illustrate the particular point being discussed. It should be pointed out that the new demand on the grid tariff would be charged at a less figure than £3 10s. per kW and would be at one of the "increment charges." It will not be difficult to show that large-scale domestic electrification produces a higher load factor than 40 %, and that the diversity value taken is exceeded in actual practice. From this it would appear that the fear that normal domestic tariffs will not produce an economic return if development proceeds are without real foundation.

Wimbledon is a good example of an undertaking which has developed its domestic load on a large scale. Table 5 gives the units sold under various headings over a series of years covering this development of the domestic load. The large development of the domestic load indicated in Table 5 has been accompanied by an increase of undertaking load factor, and it is interesting to estimate what is the approximate load factor of the domestic units. For this purpose, assume the following load factors: public lighting, 45 %; private lighting, 12·5 %; power, 25·0 %. Applying these load factors to the 1936 units, the following maximum loads accrue: public lighting, 434·57 kW; private lighting, 9 515·56 kW; power, 5 460·91 kW; total, 15 411·04 kW. Deducting this from 23 652 kW (the maximum load of the undertaking) leaves 8 241 kW, which gives a load factor of 49·8 % for the domestic units. The power units are sold to factories having a normal working week of 47 hours. It will be seen that the load factors assigned to the other classes of supply are rather on the high side, and this rough analysis shows that the load factor resulting from large-scale domestic supply is of a much higher order than is usually considered possible. This conclusion is borne out by the load factors of the author's undertaking given in Table 3, and the results in Table 1.

As regards diversity values, winter and summer load curves for the author's undertaking are given in Figs. 1 and 2, covering a period of domestic-load development. Even a casual inspection of the curves will reveal that high orders of diversity between domestic and other classes of load obtain in actual practice. Curves for two days are given for the winter peak of 1936, as the shape of the curve on the day of the undertaking's maximum load was somewhat different from that relating to the normal day.

The author is of the opinion that there need be no hesitation in going forward with domestic electrification on a large scale, with relatively low tariffs.

Table 5

UNITS SOLD BY WIMBLEDON UNDERTAKING

Year	Total	Public lighting	Private lighting	Power	Domestic	Maximum load	Load factor
						kW	per cent
1924	8 570 130	482 590	3 336 209	2 822 747	1 928 584	4 440	22·03
1930	25 388 075	663 721	6 939 012	5 712 243	12 073 099	12 600	23·00
1936	60 041 806	1 713 075	10 419 542	11 959 398	35 949 791	23 652	28·9

TARIFFS FOR DOMESTIC SUPPLY

If domestic supply is to be cultivated the first essential is an attractive tariff which includes a promotional element. From many points of view some form of two-

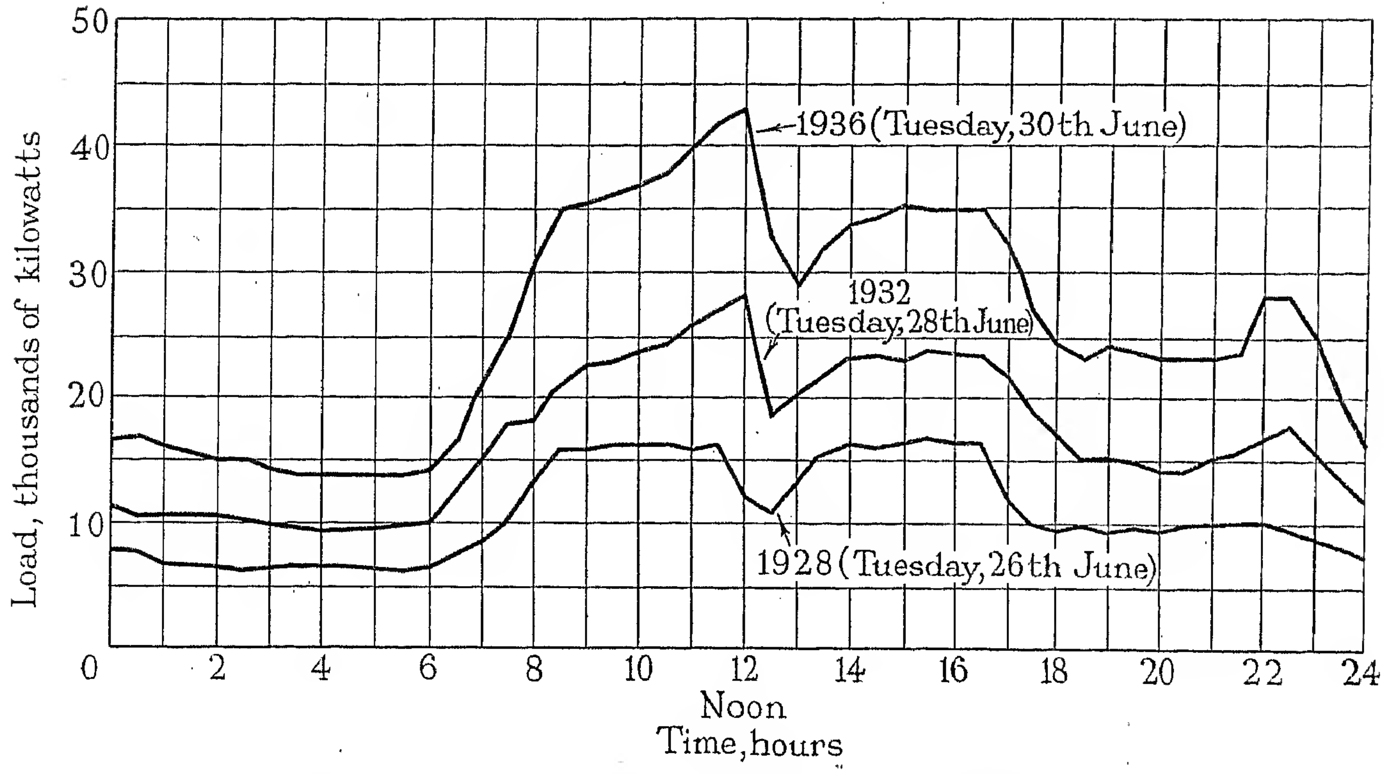

Fig. 1.—Undertaking load-curves for a summer weekday.

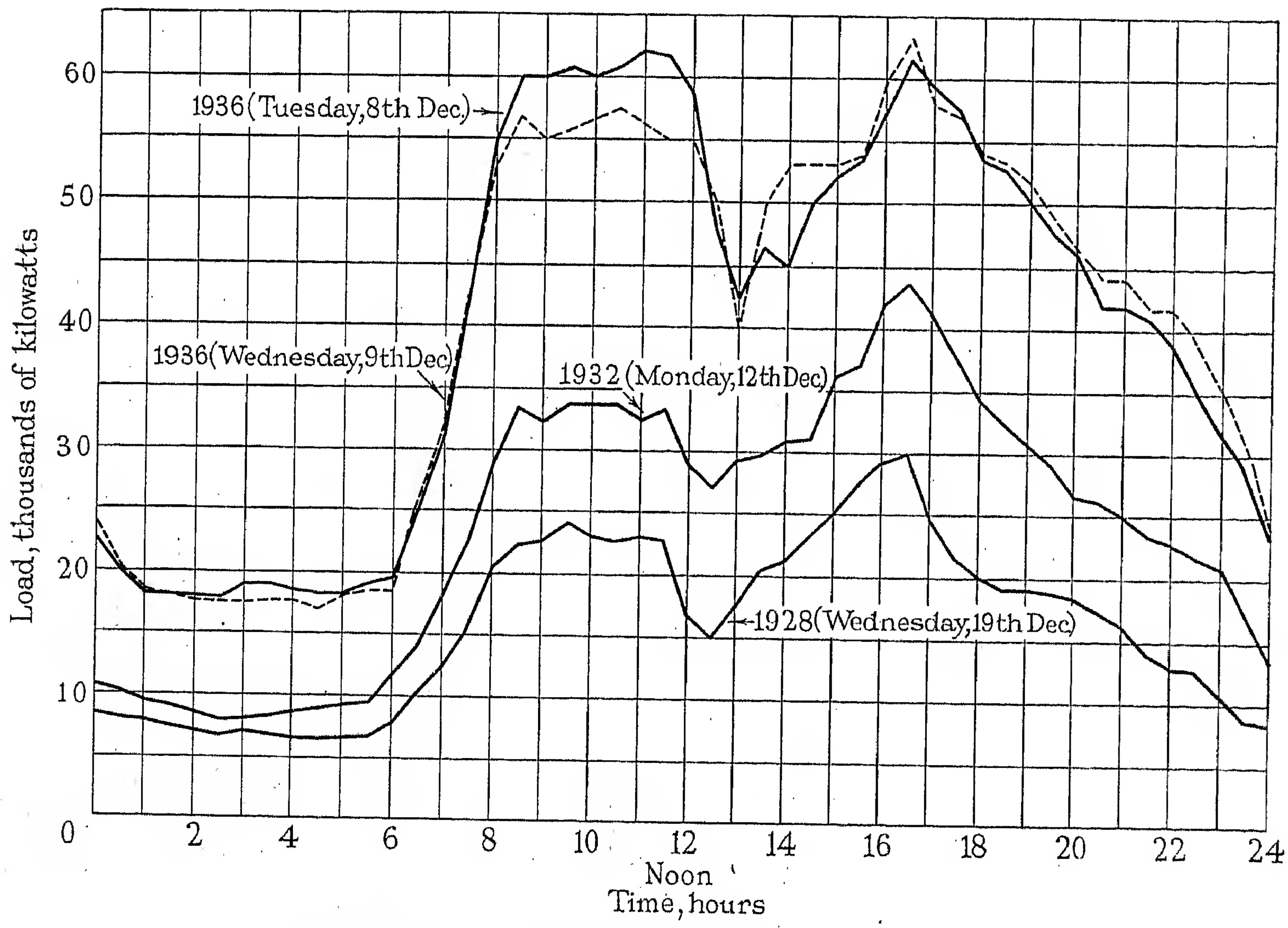

Fig. 2.—Undertaking load-curves for a winter weekday.

Year	Morning peak	Evening peak	Morning peak as % of evening peak
	kW	kW	
1928	24 200	29 900	80·93
1932	33 600	43 800	76·71
1936 (8 Dec.)	62 000	61 500	100·07
1936 (9 Dec.)	57 500	63 000	91·27

part tariff with a low follow-on rate is preferable to the graded block system. In the two main forms of two-part tariffs in use the standing charge is based on either (*a*) number of rooms or size of house or floor area; or (*b*) rateable value. There are other forms of tariffs in use for special classes of houses, such as the so-called "all-in" tariff in use at West Ham and other towns. Although these have done good service in special cases, they are not suitable for general application. They have been devised to meet the needs of a particular class of consumer. Many years ago, after a careful review of many forms of tariffs for domestic supply, the author came to the conclusion that the rateable-value form was as good as any other and had less disadvantages than most. It has the merit of simplicity, is capable (with safeguards) of general application, and does not require a special visit to the particular consumer's premises. The last feature is of great value when dealing with a prospective consumer, for the sales staff can inform him immediately what the standing charge will be.

Table 6

UNITS SOLD UNDER DOMESTIC TARIFF

Year	Millions of units	As percentage of total units sold	Average price
			d.
1929	3·7	4·91	1·84
1930	4·5	5·28	1·75
1931	8·7	8·59	1·30
1932	14·6	13·08	1·16
1933	20·7	17·27	1·09
1934	24·5	18·85	1·09
1935	28·9	19·48	1·07
1936	37·8	22·17	0·97
1937	46·7	24·17	0·97

The following description of the details of the rateable-value tariff as applied in the Hull area may be of interest: (i) The standing charge is 15 % of the rateable value in the city area. The suburban and rural areas are zoned, and the standing charge is raised to 17·5 % or 20 % according to distance. (ii) The assessments taken are those obtaining during a particular assessment year, so that a general change in assessments does not affect the electricity account. (iii) To prevent the standing charge becoming prohibitive for houses with high assessments, a reduction is made in the percentage on the amount by which the assessment exceeds £40 per year. (iv) To prevent the tariff being used to get cheap lighting units in houses with low assessments, the minimum period of use is 1 year, and the minimum account for any one year is £3. The minimum is spread over the four quarters, £1 per quarter being charged for the two winter quarters and 10s. per quarter for the two summer quarters. (v) The unit charge is ½d. per unit for the first 360 units per quarter, and ⅓d. per unit for all units over. This unit rate is common to all consumers on the tariff throughout the area. (vi) To cater for the poorer class of consumers, in some cases the standing charge is collected with the rental of the house, and a slot meter, calibrated for 2 units per penny, installed. Where it is not possible to collect the standing charge with the rent, plain slot meters are installed, calibrated at various rates, so that the amount in the meter for the usual consumption of the house brings in slightly more than the tariff. The excess is returned to the consumer. When there is a consistent deficit, the calibration of the meter is altered, and the deficit made good. Whatever the method, all domestic consumers pay on the same tariff.

The results of sales under this tariff for the author's undertaking are given in Table 6. Equally good results have been achieved by other undertakings with a different form of tariff, which may be taken as reasonable proof that the particular form of tariff is not important. What is important is the price paid.

The protagonists of any form of tariff should remember that no tariff in general use can give strict equity to all the consumers using it. The actual value of the fixed charge in a two-part tariff depends entirely on the diversity factor of the group which is being given supplies under the tariff, and any change from the average diversity value renders the standing charge inequitable. No form of tariff can be ideal, so that it really becomes a matter of choosing the form which appears to have the least objections—and which will develop sales.

It will be generally admitted that, as a general rule, increase of output decreases costs per unit, and new uses for electricity supply increase the diversity between different classes of demand, and so again decrease costs. It is well worth while to offer relatively low tariffs in the domestic field, for it has illimitable possibilities.

THE PLACE OF THE ELECTRIC COOKER IN DOMESTIC ELECTRIFICATION

The great majority of dwelling houses in this country are inhabited by the working class, who have a very limited income. In the City of Hull 85 % of the houses are assessed at £15 or under, whilst 58 % are assessed at £10 or under. It is reasonable to assume that the percentages for this country as a whole will not be greatly different, and it follows that domestic electrification must cater for the working-class house.

Lighting and cooking are required in every house, whatever the income limit, and therefore every house is a potential consumer for electric lighting and cooking. The degree in which other forms of electric service are adopted is more likely to be restricted by income than will be lighting and cooking. From the foregoing it would appear reasonable to conclude that the domestic cooker is the apparatus which can produce the greatest sale of units in the household field at the present time. On the author's undertaking 15 538 cookers have been placed in service in less than 8 years, and 85 % of these are in working-class houses. It has been demonstrated beyond dispute that cooking by electricity is as cheap as any other method available, and therefore there is no valid reason why every house within a supply area should not be equipped with an electric cooker.

It should be pointed out that in rural areas the conditions are more favourable to the sale of electric service than in urban areas. This is reflected in the statistics from the author's undertaking which are given in Table 7. When the supply is used for lighting only, the

figures are practically the same for houses inside and outside the city boundary.

The author regards the electric cooker as the most valuable piece of apparatus in the campaign for domestic electrification, despite the fact that often, owing to the innate conservatism of the average housewife, it is the most difficult of all electrical services to get adopted.

Table 7

AVERAGE UNITS SOLD PER CONSUMER ON THE DOMESTIC TARIFF FOR THE YEAR 1936

Rateable value	Within the city boundary	Outside the city boundary
£15 and under	666	1 131
£16 to £30	1 253	2 254
£31 and over	2 973	4 725
All houses	904	1 796

MARKETING THE ELECTRIC COOKER

So far as working-class houses are concerned, very little consideration is required to arrive at the conclusion that the only possible way of marketing electric cookers is by means of straightforward hire or rental, which should include the provision of the necessary wiring and of the control switch. Much controversy has arisen as to whether all the costs appertaining to cookers and other forms of domestic apparatus should be covered by the rental, or whether some or all should be included in the charge for electrical energy. The chief objection to including the rental in the energy charge is that the addition to the normal charge for energy must be based upon the average consumption; thus, the consumer who uses less than the average will not pay sufficient to cover the costs, whilst the consumer who uses more than the average pays more than the true cost. This objection applies to all tariffs for electricity supply in some degree, but there is a distinct difference in this respect between tariffs and rentals. With tariffs, it is both impossible and impracticable to ensure that the charge to each individual consumer bears the same relationship to costs; therefore the costs are averaged out for groups having similar conditions, and the tariff reflects the average costs. With cookers and other forms of apparatus, it is possible to ascertain the true average cost of each form of apparatus, and to cover this cost in the rental.

If the market can be properly developed with a true economic rental, it would appear desirable to adopt this method, for then a proper check can be kept of the economic results; but it appears that if a true economic rental were charged direct, this would tend to restrict progress, and therefore most undertakings which have developed the cooking load have used rental values below the true economic ones, depending on the sales of energy for cooking to redress the balance.

In Hull the rental of apparatus is in a number of cases collected weekly with the house rent. In other cases a variation of the " all-in " tariff with a slot meter is used, but in all cases the standard rental is paid by the consumer.

Domestic electric cooking is relatively an innovation, and it will not be generally adopted unless the supply undertaking fosters its development. This means that advertising, demonstrations, and canvassing must be undertaken on a proper scale and pursued consistently. The best advertisement is a satisfied user, and therefore considerable care should be taken to ensure satisfaction after the cooker has been installed. The installation should be followed immediately by a visit from a lady demonstrator. The demonstrator's main object is to explain how to use the new cooker—not to show the housewife how to cook, as that might be regarded as an insult. The advantages of proper cooking-pans should be brought to the notice of consumers, both at the time of booking the order and by the demonstrator. The necessary cooking-pans should be stocked and sold. A further visit should take place after a month or two, when any difficulties which may have arisen should be smoothed away. The training of the sales staff should include their being taught to appreciate, so that they, in turn, can make the consumer appreciate, that an electric cooker is a new kind of household tool which requires in its use a somewhat different technique from its predecessors.

A very complete servicing department should be available, and arranged so that any defects are attended to immediately. Prompt attention is well worth while. The question of quick boiling of small quantities of water can best be dealt with by getting cooker consumers to have an electric kettle as well. Practically all the author's cooker consumers hire an electric kettle at the same time as the cooker is hired. The cooker control board is fitted with a plug point for this purpose, and in consequence very little has been heard of this particular difficulty, which seems to have caused trouble in many places.

Different localities may need different methods as regards both tariffs and rentals. If the methods adopted bring in a satisfactory volume of business they may be regarded as correct, whether they are unique or otherwise, for the final criterion is " Does it work ? " To-day, the domestic electric cooker is a reasonably good and reliable piece of apparatus, and if an undertaking is not making progress with this important phase of electricity supply the fault does not lie with the cooker.

THE CHOICE OF THE COOKER

When hiring on a large scale is adopted, if the types, makes, or outward appearance of the cookers available for hire alter, troubles will ensue from consumers wanting to have their cookers changed. This was brought home to the author when, after over 7 000 partly black stove-enamelled cookers had been installed, it was realized that the all-vitreous-enamelled cooker had " arrived," and that the sooner it was adopted as the standard the better. No sooner were the vitreous-enamelled cookers available than the undertaking was inundated with requests for the existing cookers to be changed for newer models. The position was partly met by reducing the rentals of the earlier models, and by instituting a fee for the change of cookers at the request of the consumers.

A permanent cure was effected by gradually changing the stove-enamelled parts to all-vitreous-enamelled ones.

When considering the matter at the start, the author decided that four sizes were necessary to satisfy the household requirements of his area, and experience has shown that this decision was correct. He also decided that, so far as was practicable commercially, one make of cooker only was desirable, for the reasons given in the preceding paragraph. To-day, all the cookers in use in the area are of one make, and all the various sizes of cookers are outwardly similar. Changes have taken place in elements, boiling-plates, etc., but the changes are not noticeable to the normal consumer. The author's standpoint with the manufacturers is that, while he does not desire to check development, any proposed change that would be noticeable to the consumer must have very substantial economic or practical reasons in its favour before it can be considered, and if the reasons appear to be sufficient a large-scale experiment will be made to ascertain whether a change is justified.

Many municipal supply undertakings make a practice of advertising each year for contracts for their cooker supplies, and by accepting tenders for different makes in different years provide the undertaking with a serious problem in regard to its consumers, and also in regard to spares. In the past it has been thought legally necessary to advertise; to-day it should be well known that the law does not necessarily require this, and if the Standing Orders of the municipality require it then it is time such Orders were revised. Standardization is obviously desirable, and standardization and yearly contracts for this purpose are not compatible. Tenders put forward in response to public advertisements do not necessarily bring the lowest price to-day, for many products. The policy of restricting purchases to one make, and negotiating the purchase price with the manufacturer as and when necessary—preferably a review each year—gives as favourable a purchase price as any other method.

The progress of a rental scheme will be influenced by the rental charged. The lower the rental the better the chance of progress. The rental is bound to be proportional to the first cost, so that first cost, while not the most important, is a very important factor to be taken into account when choosing a cooker. Supply undertakings are therefore anxious to get their supplies of cookers at the lowest price compatible with proper performance and reliability. The price at which a manufacturer can supply is governed partly by volume of output and partly by how far that output can be produced by mass-production methods. Any changes, whether in essentials or details, interfere with the regular flow of production and put up the cost, not only of the particular jobs on which changes are made but also of the whole production of the works. For this reason purchasers should refrain from specifying details differing from a manufacturer's standard production. An efficient cooker manufacturer has a far better knowledge of the requirements of a cooker than any supply engineer can hope to find time to obtain, and has to study every detail of his product with great thoroughness, so as to produce the optimum product in a competitive world.

The final judges as to whether or not electric cookers are satisfactory are the users, and the users are the housewives, not the engineers of supply undertakings. Realizing this, when the choice of cookers came up for decision, the author first obtained the opinions of housewives regarding the various makes. This was done by getting a standard cooker from each of the leading manufacturers, installing them in houses, and leaving them for about 3 weeks. The cookers were then changed from house to house, until each housewife had actual cooking experience of each cooker. Each time a change was made the housewife's opinion of the cooker was obtained and tabulated. At the end of the trial period it was found that practically all the users had awarded preference to three makes. Then, and not until then, were maintenance staff invited to make a careful survey of the three makes, with a view to deciding which appeared to be the best from an engineering standpoint, with special reference to consumption, and ease of replacement of elements, etc. It was found that the three were about of equal merit; the choice therefore became quite easy, and was made finally on the basis of first cost.

No attempt was made to determine the relative merits of top, bottom, and side heating for ovens, or the optimum speed of boiling-plates, grills, etc., as it was surmised that the average housewife would not be particularly interested in such matters. Whilst an engineer's opinions on these matters may be interesting, they cannot be regarded as conclusive in any way. What is wanted is a cooker which will satisfy the reasonable requirements of the average user, at the lowest price consistent with reasonable reliability. Any competent cook can demonstrate that equally satisfactory oven cooking can be done with any one of the various arrangements of oven elements, so that it appears hardly worth while to be dogmatic as to the merits of any particular arrangement.

In the grill, the electric cooker has a component which is easily superior to any household competitor for grilling purposes, and demonstrators and sales staff should be properly coached to exploit this advantage. In the past, grilling has not had much place in home cooking, for the simple reason that adequate facilities were not available. Now that proper grilling equipment is available, it should be used as a valuable selling point.

A great deal has been heard in the past about the alleged shortcomings of boiling-plates on domestic electric cookers, generally based on a comparison between the time taken to boil a small quantity of water on a gas ring and the time taken on an electric boiling-plate. The critics of the boiling-plate are evidently not students of human nature. In the days when the coal fire was the only means of cooking, the householder had to adjust his habits to the known limitations of a coal fire, and did so. When gas cookers became available, the habits of the householder changed to accommodate themselves to the possibilities provided. Once people have become accustomed to the possibilities of an electric cooker, their habits adapt themselves to its possibilities. The number of times when a small quantity of hot water will be required in a violent hurry are very few indeed as compared with the normal occasions of use when ample time is available. Normally, it is quite immaterial whether the vegetables are put on to boil at 12.30 or at

12.35 p.m. The housewife will adjust her habits to the means at her disposal, and, having done so, will forget all about quick boiling. As an indication of this, the following experience may be cited. The water in the author's area is such that boiling produces a very hard scale. When kettle hiring was started, concern was felt at what would be the effect of scale formation on the life of kettle elements in normal use, and inspections were made at intervals for the purpose of organizing the necessary servicing. At the end of 2 years' service, 12 kettles were withdrawn from service, and as they were withdrawn the consumers were asked for their comments, which were written on a tab and tied to each kettle. One kettle was much more heavily scaled than the others and its boiling time was nearly twice as long as that of a kettle free from scale, but the consumer's comment was " Perfectly satisfied." A quick-boiling boiling-plate is a desirable feature, but the importance of quick boiling is much overrated, and if quick boiling means a substantial increase in cost, or loss of reliability, then it is not so desirable. It should not be forgotten that many undertakings still have large d.c. networks, and the normal design of quick-boiling boiling-plate cannot be used on these. It is undesirable to have a feature which cannot be used throughout the whole supply area, and therefore, on those undertakings which still have both a.c. and d.c. networks, it is not advisable to attempt to introduce the quick-boiling boiling-plate until alternating current is available throughout the area. If a consumer attaches considerable importance to the quick boiling of a small quantity of water, other means are available to achieve this object.

A temperature indicator for the oven is a very desirable feature, and should always be fitted. The particular form is immaterial, so long as it records consistently. Automatic regulation of oven temperature is a new development which has many desirable features, and is certain to be popular with housewives. Increase in hiring charge will tend to discount this popularity. Satisfactory cooking can be done by the normal manual control, and automatic regulation may be looked upon as a good selling point, and a refinement which will be appreciated by the user. So far, the author has not found it necessary to fit it as standard, but all the cookers purchased since the time when automatic regulation was developed have been arranged so that it can be added when deemed necessary. For the poorer class of household (which forms the majority) a low rental is more important than refinements, so that it may be anticipated that the use of automatic regulation will be restricted to the larger cookers used by households where the household budget does not have to take a strict account of small sums.

While complete standardization is not possible, for many reasons, there are no valid reasons why certain features of cookers should not be standardized, and the number of sizes and shapes reduced. For instance, the size and shape of boiling-plates, grills, and oven elements, could be reduced to a relatively small number, and the method of connection by plugs made common and interchangeable. The more cheaply cookers can be produced and sold, the greater the market, and the more quickly will it be developed. Therefore it is desirable that all means to the end of a lower price should be carefully explored, in the interests of both the supply industry and the manufacturers; this calls for co-operation between the makers and the buyers.

MAINTENANCE COSTS

The term " maintenance costs " has different meanings with different undertakings. The figures given in this section are for the author's undertaking only, and are believed to include every item of cost incurred in maintenance.

The cost will be influenced by the standard of maintenance given, and by the standard of service given to defects. In this case, the cookers are maintained in a condition equal to new, including the oven plates and cooking tin, and the grill pan. Since the cooker hiring scheme started 8 years ago, in the author's area there have been great developments in house building owing to the modern demand for houses on the garden city plan, and to slum clearance schemes, etc. This has resulted in an abnormal number of changes of tenancy. At each change of tenancy it has been deemed advisable to remove the cooker, completely de-grease and overhaul it, and put it into new condition again; new tinware has been provided before the cooker is re-issued. This has incurred a very large item of expense, which is properly chargeable to maintenance. In addition to cooker removals due to changes of tenancy, removals occur for financial and other reasons, which again inflate the maintenance costs. The serious nature of this expense is illustrated by the figures given in Table 8. The figure for total removals, expressed as a percentage of the gross total of cookers installed, is 26·8 %. The following is an analysis of the causes of removal: changes of tenancy, 14·0 %; financial reasons, 8·2 %; other reasons, 4·6 %; total, 26·8 %.

Table 8

Year	Total number of cookers in use	Removals (already deducted from total)	Percentage of removals to total
1931	2 174	46	2·1
1932	4 938	414	8·4
1933	6 592	971	14·8
1934	7 406	1 150	15·5
1935	8 673	963	11·1
1936	12 010	953	7·9
1937	15 538	1 192	7·6
Total removals		5 689	

The cost of removing and reconditioning for the last two years, 1936 and 1937, was £4 773, which is 27·9 % of the total maintenance cost for those years, and gives an average of £2 4s. per cooker removed and reconditioned. Comparing the total maintenance cost with the average number of cookers in use, it works out at 3s. 11d. per cooker per annum. (The term " average cookers in use " implies the mean of the number in use at the start and finish of a financial year.) It should be

Table 9

COOKERS CONNECTED, AND CAPITAL COST

Year	1930	1931	1932	1933	1934	1935	1936	1937
Cookers connected during year	239	1 935	2 764	1 654	814	1 267	3 337	3 528
Cost of cookers .. (£)	2 440	18 562	23 809	13 686	7 045	11 442	26 672	27 338
Cost of wiring, fixing, transport, etc. .. .. (£)	833	6 776	9 141	6 442	4 586	5 928	13 229	15 046
Total capital .. (£)	3 273	25 338	32 950	20 128	11 631	17 370	39 901	42 384
	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.
Average cost of cooker ..	10 4 2	9 11 11	8 12 3	8 5 6	8 13 1	9 0 7	7 19 10	7 15 0
Average cost of connecting	3 9 9	3 10 0	3 6 2	3 17 11	5 12 8	4 13 7	3 19 4	4 5 3
Total average cost	13 13 11	13 1 11	11 18 5	12 3 5	14 5 9	13 14 2	11 19 2	12 0 3

explained that the shop arrangements for reconditioning were somewhat of a makeshift order, owing to overcrowding. When it was realized that for some years it was to be expected that about 1 000 cookers per annum would have to be handled, proper arrangements were made to carry out the work, and in the future the cost will fall substantially.

It appears reasonable to assume that the percentage of cooker removals will decrease in the future, for the present rate of house building cannot continue indefinitely, and also, as progress is made, the number of removals due to financial and other reasons will fall, as the unsatisfactory consumers will become known and will be eliminated; so that this important section of the maintenance cost should decrease substantially, and for this reason it is shown separately in Table 11.

So far as service is concerned, a high level is maintained. Throughout the week, including Saturdays and Sundays, trained men are on duty from 8.0 a.m. to 11 p.m. to attend solely to cooker faults. Four men are on duty from 8 a.m. to 4 p.m., and two men from 3 p.m. to 11 p.m. On Sunday, one man only is on duty, with others available on call if wanted. Each man is provided with an electric vehicle equipped with all the spares which experience has proved necessary. Immediately any cooker fault or trouble is notified, a man is despatched and the fault put right. On completion of the work, the man goes to the nearest telephone and finds out whether any other fault has been reported. If so, he proceeds direct to the fault; and if not, he returns to headquarters. The actual working time of the men is not very high, and it is anticipated that the existing staff will be sufficient for some time. It will even be adequate when the total number of cookers in use is much greater than at present, so that the cost of wages and transport for faults should tend to fall in the future. Immediate attention to faults is necessarily somewhat costly, but it is the only way to ensure satisfied consumers.

The capital expenditure on cookers, which has all been met out of revenue, is given in Table 9.

The totals and averages for the totals from Table 9

Table 10

Location or type of fault	1936	1937
Boiling-plates	2 494	1 766
Grills	1 420	1 141
Oven elements	862	944
Thermometers and heat indicators	886	894
Inefficient heating ..	378	305
Low voltage	9	12
Sockets, etc.	321	322
Circuit switches	462	348
Circuit fuses	655	524
Internal wiring	520	425
External wiring	193	205
Damaged enamel	—	—
Breakages	446	460
Fittings	727	722
Tinware (cooking plates) ..	721	437
Lagging	18	89
Shock	65	25
Fire	—	3
Main switches	119	95
General overhaul	7	2
Unclassified	636	620
No fault	1 720	867
Totals	12 659	10 206

as at the 31st March, 1937, are: Cookers in use, 15 538; cost of cookers, £130 994; cost of wiring, connecting, etc., £61 981; total capital cost, £192 975; average total

capital per cooker, £12·4. The cookers are made up of the following sizes: "juniors," 6 170; small, 7 095; medium, 2 010; large, 263; total, 15 538.

While the detail costs of maintenance are available for the whole period, no useful purpose would be served by giving them in this paper, for the earlier years would not be a reliable guide, but the total maintenance costs per cooker for the respective years, including cost of removals, are as follows: 1930, 2s. 3d.; 1931, 3s. 6d.; 1932, 5s. 3d.; 1933, 10s. 3d.; 1934, 9s. 4d.; 1935, 10s. 11d.; 1936, 15s. 3d.; 1937, 13s. 5d.

salaries and wages, cost of stores, etc. No management charges are included, but every expense incurred is embodied in the costs, including salaries, or proportions thereof, of the supervisory staff actually engaged on cooker work. The figures given are the actual total costs incurred. A two years' average is a safer guide than the costs for one year, for fairly wide differences occur on some of the items, even when allowance is made for difference in numbers for the two years.

It will be seen from the various figures given that maintenance costs have about reached the peak value,

Table 11

MAINTENANCE COSTS

	Total cost for 1936	Total cost for 1937	Total costs for two years
	£ s. d.	£ s. d.	£ s. d.
Boiling-plates	967 10 5	1 079 14 2	2 047 4 7
Oven elements	450 15 9	282 5 9	733 1 6
Grill elements	488 9 10	442 18 0	931 7 10
Switches, pilot lamp, etc.	238 3 0	213 10 0	451 13 0
Replacement of non-electrical equipment	1 323 10 3	1 126 9 11	2 450 0 2
Cooker bodies	876 0 5	679 19 6	1 555 19 11
Main switches and wiring	97 8 11	66 0 8	163 9 7
Miscellaneous	803 18 8	1 890 19 11	2 694 18 7
Transport	891 9 10	412 11 3	1 304 1 1
Totals	6 137 7 1	6 194 9 2	12 331 16 3
Changing and removing	540 17 5	606 10 1	1 147 7 6
Reconditioning	1 219 6 6	2 406 14 3	3 626 0 9
Totals	1 760 3 11	3 013 4 4	4 773 8 3
Total maintenance cost	7 897 11 0	9 207 13 6	17 105 4 6
	1936	1937	Average for two years
Average number of cookers in use for period	10 341	13 774	12 105
Maintenance cost per cooker per annum	11s. 10d.	9s.	10s. 2d.
Changing and reconditioning costs	3s. 5d.	4s. 5d.	3s. 11d.
Total maintenance cost per cooker per annum	15s. 3d.	13s. 5d.	14s. 1d.

The record of faults and defects attended to for the years 1936 and 1937 is given in Table 10. Sometimes more than one defect is attended on a visit, and therefore the totals do not represent the number of visits made.

The maintenance costs incurred over the last two years are given in Table 11. The wide difference between the transport costs for the two years is mainly due to a new electric vehicle having been bought during 1936, the full cost of which is charged in that year's accounts. The wide difference between reconditioning costs is due to many cookers removed during 1936 not being reconditioned during that year but during 1937.

The costs assigned to the various items include wages for the time spent, and also a proper proportion of

and, for the reasons already advanced, it is anticipated that the future will see a substantial reduction in maintenance costs. It should be stressed that the figures relate to cookers which are maintained in a condition equal to new, and where a high standard of service is maintained. Decreasing the standards would decrease the costs, but the author does not consider it advisable to do this, as satisfied consumers are the main object of his undertaking.

Every possible step is being taken to get the costs down to a lower value, and it is confidently anticipated that appreciable reductions can be made, but even on present values there does not appear to be any cause for alarm. Cooking is only one part of domestic electrifica-

tion, and the other appliances which are normally hired out, such as water heaters, wash boilers, kettles, etc., have relatively low maintenance costs attached to them, so that relatively low rentals are economic in their case. A very small margin on the energy cost used by cookers will cover any subsidy required, so that the total received for rental and energy will cover the total costs.

LIFE OF DOMESTIC COOKERS

In the early stages of the development of domestic cookers many opinions were expressed as to the probable economic life, and a figure of 7 years was often taken as the basis for the sinking fund or depreciation. On the author's undertaking some of the cookers have been in use for nearly 9 years, and in appearance and performance they are quite as good as new cookers. The all-vitreous-enamel finish has considerably extended the economic life. With a high standard of maintenance the life of a modern domestic cooker appears to be indefinite. Improvements and changes of fashion may put a definite period to the life, but the present data would indicate that, under the conditions postulated, it would be justifiable to take 20 years as the economic life for calculating the depreciation allocation. Thus a high standard of maintenance does lighten the burden of depreciation.

CONCLUSIONS

In dealing with the problems of economics involved in the hiring of domestic cookers the economics of the whole of domestic supply should be taken into account. When this is done, there is no doubt that domestic electric cooking, with the cookers hired out at rentals low enough to attract consumers, can be made an economic proposition.

For many years now, there has been growing the conviction that electricity is, or can be made, a great social service, which can be organized so as to provide valuable assistance for all sections of the community. All schools of political thought are subscribing more and more to this ideal. Thus electricity supply is coming to be regarded as something more than a business. The 1919 Act, the 1926 Act, and the proposed new legislation, are all evidence of this new orientation of thought, which is placing those in control of electricity supply in the position of trustees, charged with the duty of providing all possible service to the community they serve at the lowest possible cost. Domestic supply is undoubtedly the largest field for this service, when judged as to possible benefits to the community. It therefore becomes the duty of all undertakings to provide attractive domestic tariffs, backed with hire and hire-purchase schemes, and a high standard of service, which will enable all classes of the community to receive the manifold benefits of electrical service in the home.

Cooking is only one section of that service, but it is probably the most important section of the service from a housewife's point of view, and therefore warrants the most careful thought and consistent effort to provide a complete service at a cost which is within the reach of all.

The author's thanks are due to Mr. A. E. McKenzie, chief engineer and manager of the Corporation Electricity Department, Wimbledon, for the statistics in respect of Wimbledon on which Table 5 is based.

[The discussion on this paper will be found on page 595.]

DISCUSSION ON THE PAPERS BY MR. HUMPHREYS (SEE PAGE 565) AND MR. WAITE (SEE PAGE 583)

BEFORE THE INSTITUTION, 20TH JANUARY, 1938

Mr. J. W. J. Townley: The recent development in the use of electric cookers has not been in the direction which many of us expected a few years ago, namely among the middle-class population of this country, but among the very poorest classes of the community. As an illustration of this I would say that in my undertaking, where there are now about 13 000 cookers in use, last year £130 000 was collected from prepayment meters.

Referring to Mr. Humphreys's paper, I wish we could agree upon a standard method of design for electric ovens. We want the simplest possible form of cooker, so that the housewife may know that by following the instructions in a standard handbook she can get uniform results. A frequent source of complaint is the consumer who comes into an area where the standard oven has side-heating and bottom-heating, and complains that she cannot equal the results that she got with the cooker previously used in another supply area which may have had side-heating only.

I was interested in Mr. Humphreys's remarks on vents. Adjustable vents become clogged with grease. I have examined many cookers on return from hire, and in about 90 % of cases the vents are no longer adjustable. I therefore prefer fixed vents, suitably designed and beyond the control of the user.

It is particularly necessary to ensure adequate earthing of the framework of boiling plates. I have had trouble due to plates becoming alive because of unsatisfactory bonding. This is a matter to which supply engineers and manufacturers should give their attention.

A short time ago I would have chosen the radiant-heat boiling-plate in preference to other types, because of the housewife's desire to see something red and glowing, but nowadays I find that the electricity consumer is beginning to realize the convenience and, generally speaking, the satisfactory results obtainable from the dull boiling-plate provided that it is of sufficient loading.

Mr. Waite's paper indicates a greatly increased domestic load during the last few years, and his figures relating to load factor are almost precisely the same as my own. In the last 5 years we have added about 75 000 kW of electric cookers, and the load factor has increased during that time from 34 % to 45 %. This load-factor improvement has not been entirely due to the additional cookers, but it is obvious that they have not had an adverse effect.

I think that the question of service is quite as important as that of supplying a satisfactory cooker. Mr. Waite's system of rapid service is similar to one which has been in operation in my undertaking for many years and has proved very successful. A service-man gets a call to a certain area, and before returning to the depot inquires by telephone whether any other call has been received. He may then receive notice of a complaint from a neighbouring street, and frequently he will arrive there to attend to the complaint before the complainant's messenger has returned from the telephone to say that the message has been given to the electricity undertaking.

Mrs. K. Pocklington: Mr. Waite's paper says that the necessary cooking pans for use with electric cookers should be stocked and sold. Referring particularly to low-cost houses, it would be extremely helpful if supply authorities could be persuaded to increase slightly the hire charge for the cooker and include a set of correct utensils, so as to ensure that the consumer obtains the highest possible efficiency from the cooker.

Mr. F. H. Clough: Mr. Waite explains why it is necessary to hire cookers to the consumers, and Mr. Humphreys indicates how hiring affects the design. Must a hiring system necessarily depress the quality of the cooker? Could not a better article be supplied and still show a lower total cost of operation?

Mr. Waite gives figures from which it can be deduced that the annual charge due to the cost of the cooker is about 15 % of the total annual cost of operation. If the cooker were increased in cost by, say, 20 % the total cost would only go up 3 %; but by making a better and slightly more expensive cooker, savings in maintenance and power consumption could be made, which would offset this increase several times over and thus give a lower total annual cost than at present.

Some of the increased cost could be devoted to improvement in details which both maker and user would like to have, and the rest to fitting temperature control.

With temperature control, the limits in design imposed by the possibility of a high "run-away" temperature, due to the switch being left in the "high heat" position inadvertently, are removed. The oven can be provided with better heat insulation, with corresponding saving of losses and power consumption. The oven elements can be more robust, as they can be connected permanently in series and need not be divided into small sections for series-parallel connection. These more robust elements, running at a lower temperature, will eliminate oven-element replacement. The same elements can be used for a reasonable range of voltage, which will reduce stocks and help manufacture, and, of course, the temperature will not be appreciably affected by voltage variation. Finally, the user gets an article which will cook better.

Mr. J. I. Bernard: Mr. Humphreys suggests that the heating condition of an oven should be designated by a number instead of by a temperature scale, as is done in the ordinary way with an oven-heat thermometer; I think it is questionable whether this is desirable. Everyone has some conception of what temperatures are in

degrees Fahrenheit, but an arbitrary number introduces a good many difficulties, shown by the fact that the correct calibration for each type of oven has at present to be determined by actual cooking tests. I would suggest that temperature indicatiors are more straightforward, and have the advantage that they correspond to the thermometer readings which are already given in electric cookery-books. In the gas industry in this country thermostats are calibrated quite arbitrarily nowadays, and six different scales have been adopted. This is not a good example to follow.

I wish the author had discussed the effect of variation in loading of the oven elements. The thermostatically-controlled ovens which are used in other parts of the world have higher loadings and shorter preheating times than the normal British cooker, and it may be that the introduction of thermostatic control will lead to shorter preheating times for cookers in this country also.

In regard to Mr. Waite's paper, the deductions which the author draws as to the load factor of the domestic load, taken from the figures for his own undertaking and that of Wimbledon, should be accepted with the qualification that in these two undertakings particular care has been taken to develop those domestic loads which are most desirable, namely cooking and water-heating. In Mr. Waite's own undertaking a large number of cookers are connected, and in Wimbledon there are a large number of water heaters, in the proportion of 1 to every $2\frac{1}{2}$ consumers at the present time. These figures indicate that the highest load factor from the domestic load is only obtained as a result of planned development.

Mr. Waite has thrown a great deal of light on the much-debated subject of cooker maintenance cost. Many supply engineers were formerly deterred from adopting cooker hire schemes because of reports from other undertakings which had had experience of the matter that maintenance costs were too high, figures up to £2 or £3 per annum per cooker being quoted. It has since been made clear, by some systematic analyses of maintenance costs carried out by the British Electrical Development Association, that when cooker maintenance costs are given on the basis of keeping the cooker in service, and not making an allowance for the reconditioning of the old black cookers which were so largely in use in the early days, the figure is very much less. The figures which Mr. Waite gives on that basis are, I think, quite representative, and his total maintenance cost when removals are taken into account seems very reasonable.

Mr. A. F. Harmer: Dealing with Mr. Waite's remarks on tariffs (page 588), I do not approve "all-in" tariffs (sometimes called "equated"), as they apply unfairly to good consumers, in that the more electricity is used the more is paid for the apparatus. A standing-charge figure of 15 % to 20 % of the rateable value seems very high, although, of course, the actual charge is dependent on the local assessment. The corresponding figure in Hammersmith is only $6\frac{1}{2}$ % (net), with a running charge of 0·425d. (net). To modify the standing charge where the assessment is high seems to indicate a possibility of preferential treatment. I do not favour collection of the standing charge with the rent, as this practice renders the weekly rent of a house or flat higher than that of a coal- or gas-equipped flat, with a consequential leaning of the would-be tenant to the latter. The method of charging by prepayment meter with varying conditions, as set out in col. 2 of page 588, seems very complicated. I have found in Hammersmith that the "not too well off" consumers want to "pay as they go." In order to meet this requirement, a step-rate prepayment meter has been evolved, which operates in this way: The fixed charge, made up of the rateable-value figure and the hire of cooker, wiring, etc., is, say, 1s. 3d. per week; the running charge is $\frac{1}{2}$d. per unit. Therefore I require 6 units at 3d. per unit to cover the fixed charge. The meter is arranged to collect this, starting on a Friday night when the consumer has just received his wages. As soon as the 6 units at 3d. have been consumed, the mechanism changes over to $\frac{1}{2}$d. per unit for the rest of the week.

I do not advocate the use of special, very high-priced cooking utensils. Whilst, when the pan and the boiling-plates are new, the special utensils are better than ordinary pans, within a few months the ideal intimate contact has gone, owing to pitting or buckling of the boiling-plates, and the special pans are then no better (in fact, worse) than the cheapest stock article.

I do not consider that an electric cooker requires a "different technique" from a coal or gas fire; it merely requires a little common-sense. It only frightens a would-be user to tell her she must do this and that, and have costly utensils. An electric kettle (immersion element type) of 1 500–1 800 watts should be supplied free on loan with every cooker.

Referring to "the alleged shortcomings of boiling-plates" (pages 590 and 591), I have frequently converted those who have complained of slow boiling by mentioning the point on vegetable cooking; further, the free loan of a high-wattage kettle completely clears up such complaints.

How does the author "eliminate an unsatisfactory consumer"? Does he have a black list?

Table 11 is the most truthful statement I have yet seen regarding cooker maintenance costs; quite a number of authorities seem to find allocation a difficult problem.

I must join issue with the author on the question of the life of a cooker: 20 years would be an impossible figure in my district.

In conclusion, I should like to ask the author whether he fits pilot lamps to cooker controls; if so, does he use metal-filament or neon lamps? Further, does he find that it pays to regrind pitted boiling-plates?

(*Communicated*) In order "to show them whilst they are young," I have made a practice for the last few years of supplying domestic cookers to girls' schools on loan, free of charge. I find that the girls take a great interest in cooking by electricity, and consequently urge their parents to become "all electric."

As regards reconditioning, my method is to immerse completely the entire cooker in a cleaning solution and boil for about 3 hours, then dip in clean hot water and drain off, later drying out by putting the oven elements on circuit. The cooker is then indistinguishable from a new one, and no deleterious effects on the lagging, elements, wiring, or switches, have been observed.

Mr. W. Ellerd-Styles: If anyone present at this meeting were to change places with a housewife during the summer and experience what it is to open the oven door

and get the hot, humid atmosphere in his face, I am sure that he would at once proceed to design an elevated cooker to remove that great inconvenience. With such a cooker it would be impossible to have the boiling-plate on the top of the oven, and it would have to be placed on one side. Provided with a detachable cover it would form a surface which would be useful when cooking was not going on.

Thermostatic control offsets the defects of 3-heat or series-parallel control. It cannot be doubted that the gas cooker with infinitely variable control is more convenient when manually controlled, but this advantage disappears when thermostats are fitted.

I agree that thermostat design should be based on numeral and not temperature indications. Experience shows that two ovens of different design will not give the same cooking results for the same indications on the temperature indicator. When indicating by numbers it is possible for a certain make of cooker to be calibrated by its chart to give fairly reliable results.

Thermometers cannot indicate the quantity of heat in an oven or cooker, and therefore their utility is limited.

I agree with the author's remarks apropos the advantage of using castings in cooker construction. Manufacturers of electric cookers will, however, follow the gas industry, which is turning to sheet-steel construction.

I am interested to note the trend towards vents in cooker design. In the early days one of the great points advanced in favour of electric cookers was the fact that they were practically hermetically enclosed and were therefore more economical than gas cookers. The salesman to-day has to use an entirely different argument, because the oven has to be ventilated in order to bake various classes of goods.

The question of standards of baking is rather a difficult one. I know one eminent authority whose lady demonstrator decides whether a cooker or oven is satisfactory according to whether it will bake a batch of scones. The futility of this test is apparent when we consider that scones require a dry condition in the oven, whereas a slab cake requires a humid condition. Bread and rolls require a humid condition during the early stage of baking and a dry condition when baking is nearly completed. No oven with a sealed cooking space will satisfactorily bake all varieties of foodstuffs. Baking is a drying process, and when the water is evaporated a humid condition is created in the oven which is undesirable for a variety of cooked products. This must be corrected by providing an exit in the form of a damper.

Mr. Humphreys showed a slide illustrating an oven with a bottom inlet and a top outlet, which suggests that electric-cooker design is encroaching on the sphere of gas cookers. The practice with gas cookers to-day is to have the burner at the bottom and to allow the heated products to traverse a certain circuit and then make their exit at the bottom. The alternative is to have an undamped inlet at the bottom and an undamped outlet at the top. This construction would give high-efficiency baking results and would tend to become the standard arrangement.

My experience with slag-wool lagging indicates that the chemical reaction on steel plates is more intense on the cold face of the outer casing, and only slightly affects the hot face of the inner chamber. Although the thermal conductivity of slag wool is low, increase in the thickness of the insulation improves the thermal capacity of the cooker or oven after the moisture has been expelled from the slag wool.

I am in favour of top-and-bottom heating. I recently came across a case where an electric cooker was being used to make thin pastry, and the side-heating gave an uneven result. A gas cooker with top-and-bottom heating was substituted, and uniformity was achieved.

Turning to Mr. Waite's paper, what is the estimated consumption of the electric cookers on the estate dealt with in Table 1? Hull has a municipal gas undertaking, and it would be interesting to know whether the laying of gas supplies to the houses on this estate is prohibited. Table 1 also shows that the maximum kilowatt load total has fallen about 10 % and the average consumption in units has declined approximately 20 % in 2 years; if the drop has been proportional in 1937 this position is very unsatisfactory. If such a fall has to be applied to Table 2, the income will fall to a figure approximating expenditure, and the supply will cease to be an economic proposition. As the standing charge is approximately equal to the unit charge in Table 2, a flat rate of 1d. per unit is the actual charge to the consumer. This being so, on what price of gas does the author base his statement that it has been demonstrated beyond dispute that cooking by electricity is as cheap as any other method available?

Finally, I think it would be an error to estimate the life of a cooker at 20 years. On the basis of Mr. Humphreys's assumptions the life of a cooker is 10 years.

Mr. G. O. McLean: Mr. Humphreys devotes most of his paper to the consideration of cookers from the performance point of view, whereas I hold that mechanical design is rather important. A reason given by the poorer-class housewife for not changing from gas to electricity is that the electric cooker which she can afford to hire has only two boiling-plates, whereas the gas cooker has four or even five. I suggest that the ideal from the housewife's point of view is to have practically the whole of the top of the cooker capable of being heated; or, say, a portion 18 in. by 12 in. divided into 6-in. square sections.

In referring to boiling-plate efficiencies Mr. Humphreys does not tell us what the air temperature is, or whether the times stated are measured from cold or from the moment when the plate has attained a steady temperature. I suggest that when the paper is printed in the *Journal* these facts should be clearly set out.

The figures given in Table 2 are not quite fair, since a capacity of 3 pints is taken as the criterion; if a smaller capacity were taken the exposed-resistor type of plate would be found to be superior to the other two types. I suggest that the actual efficiency figures should be stated in the paper, as there is little difference between the efficiencies of all the plates mentioned.

I should like to ask the author for information in regard to the use in America of ovens equipped with internal condensers to avoid the need for vents.

Turning to Mr. Waite's paper, I am particularly interested in the question of increasing the load factor. The Commissioners' returns for 1936 show several boroughs having an almost exclusively domestic load

where the load factor is high; for instance, Southend (42 %), Scarborough (36 %), and Harrogate (33 %).

On page 586 the author gives an illustration which I find confusing, as he equates the cost of 1 kW to the undertaking with the revenue from an average domestic consumer. Those two figures cannot be equated. Table 1 shows that the demand of the domestic consumer on the Sutton Estate was 0·21 kW on generation peak, and I should say, from my experience at Hull, that the domestic consumers' demand on generation peak over the whole of Hull is less than 0·5 kW; and yet the author relates the revenue from the consumer to 1 kW demand.

The author says that the manufacturer knows more about cookers than the supply engineer, and I agree that he does so far as design is concerned; but I would point out that the manufacturers have to get the housewives' opinions of cookers through the supply engineer.

Mr. R. B. Rowson (*communicated*): The most controversial and therefore the most interesting part of Mr. Waite's paper is headed "The Economic Aspect of Domestic Supply." I propose to confine my remarks to this section and to show that the results obtained at Hull are not of universal application, by considering some of the questions that a trustee should ask.

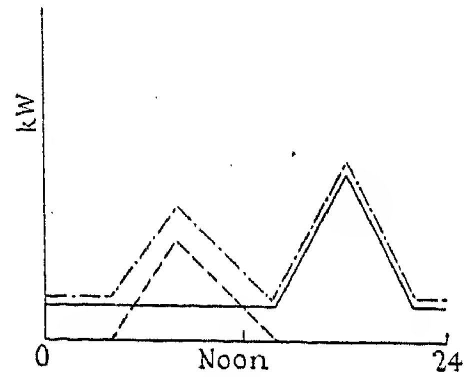

Fig. A

— — — Group 1.
——— Group 2.
— · — · System.

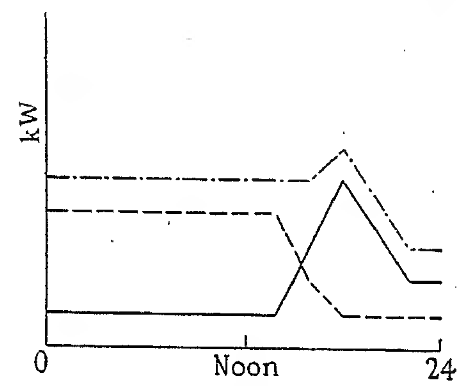

Fig. B

Graphs of peak day for the year.

— — — Group 1.
——— Group 2.
— · — · System.

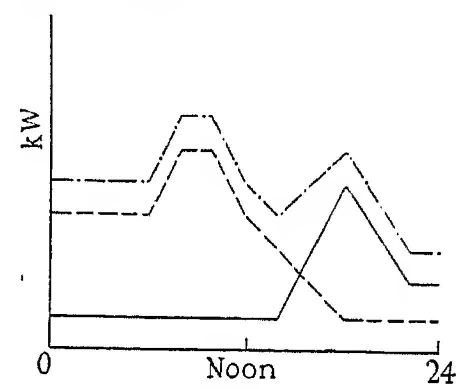

Fig. C

— — — Group 1.
——— Group 2.
— · — · System.

Mr. Waite's analogy of trusteeship is very attractive and must include the duty of holding the balance fairly between the charges made to different classes of the supply industry's consumers, of protecting the nation's capital resources from unproductive expenditure, and of avoiding nationally-wasteful competition. Thus, as regards any particular use of electricity by any group of consumers the engineer-trustee has to be able to answer the following questions:—

(1) Are existing facilities—such as gas, coal, and oil—adequately providing for the particular use being considered?

(2) If they are not, then what is the price at which electricity must be sold: (*a*) To make an electric service advantageous to the consumers, and (*b*) So that the group of consumers pay their fair share of the cost of supplying the electricity which will be required?

If the price under 2(*a*) is less than under 2(*b*), the even more complicated question of subsidy must also be considered. To give an answer to 2(*b*), the joint costs of supplying electricity must be allocated. In the paper Mr. Waite appears to retain the theory that such costs, including management, rates, etc., should be allocated, on the basis of the demand at the time of the system peak. The first question the trustee should ask is, therefore, "Should costs be allocated on the basis of peak responsibility?"* The incorrectness of the thesis is easily understood from Fig. A, which refers to a case where the whole of the system load is provided by two groups of consumers. As the peak is caused by Group 2, this group would, on the author's basis, pay the whole of the fixed charges. A less extreme case is shown in Fig. B. Here Group 2 pays five-sixths of the charges, notwithstanding the long-period use of Group 1. A difficulty with the peak-responsibility method is the effect of a change in the time of the system peak. If, for example, the load of Group 2 remains constant, but that of Group 1 grows so that it causes the peak (see Fig. C), then if costs are allocated and charges are based on peak responsibility the tariffs in force under the previous conditions will no longer comply with the formula.

The curves in Fig. 2 in Mr. Waite's paper show that in 1928 the peak was mainly due to a combination of power and lighting demand. This condition still obtained in 1937, but only just, and if the results obtained at Leicester† are any guide the cooking and power loads will cause the peak in future years. If this happens, then on the peak-responsibility basis tariffs should be changed. In this connection it would be interesting to learn what the on-peak demand of the scheme dealt with in Tables 1 and 2 would have been had the peak of the Hull undertaking for the year 1936 been at (*a*) 8.30 a.m. and (*b*) 11 a.m. on Tuesday, 8th December.

The inconsistency of the whole matter is brought out by supposing Hull to secure a consumer who would almost completely fill up the valleys and who would as a consequence take about 200 000 000 units per year. The tariff would be about 0·1748d. per unit, as Mr. Waite agrees that selling price depends on the cost of supplying and infers that costs are based on peak responsibility. The consumer would thus carry practically none of the fixed charges of the undertaking. If, however, his midnight load increased to, say, 70 000 kW, the undertaking's peak would be at this time and on peak-responsibility theory his tariff would have to be changed so that he carried about 70 % of the fixed charges.

* Perhaps the best criticism of this method of allocation is that given in the Dohery Prize Paper for 1926.
† *Journal I.E.E.*, 1938, vol. 82, p. 74.

From Table 2 it must be inferred that rates and management are allocated in the same way and are included in the £2 12s. 11d. per kW. In the case of an undertaking with as many consumers as Hull the overhead cost per average consumer cannot be much different from the total overhead cost divided by the number of consumers, i.e. £61 288/74 511 or £0·8. Thus for 500 consumers the overhead costs would be £400. I would also suggest that there is more justification for allocating rates as a percentage of revenue rather than on the consumer's demand at the time of the system peak. On the system-peak method the off-peak consumer pays no rates, which in most cases is inequitable. For Hull, rates amount to 5 % of the revenue, which for the Table 2 scheme is £95 per annum. Added to the management figure of £400 this gives a total of £495, which indicates that the allocation of £289 for " other charges " is on the low side.

Our trustee might now ask, " Are there any reasons for supposing that the results quoted in the paper may not be universally applicable ? " The answer seems to be that the results are not universally applicable, because:—

(*a*) The proportion of domestic load supplied in the case of Hull under the two-part tariff is only about 25 % of the total sales. As a consequence the effect of this load on the load curve is swamped.

(*b*) Tables 1 and 2 apply to houses where the cooker is used principally during the summer months. This invalidates the results for complete all-the-year-round electric cooking and offers no guide to the more important case of a complete cooking service.

(*c*) Table 2 is calculated on selected-station costs. If the grid tariff for S.W. England and S. Wales is substituted and coal is taken account of, unit losses being calculated at the Hull figure of 16 % of sales and kilowatt losses being taken as 10 %, the gain of £177 per annum is converted into a loss of £120 per annum.

(*d*) The assumed loss of 5 % on the kilowatts is small compared with an average unit loss of 16 % on sales, and results in a load factor of over 100 % on losses. Even allowing for transformer losses, a loss load-factor of 50 % is quite high and results in increasing the allowance from 5 % to over 10 %.

It is interesting to compare the costs given in Table 2 with those quoted by Mr. Waite in 1932.* Local distribution charges and average distribution charges from generating station to site seem to have fallen very considerably.

Having discovered that Mr. Waite's results cannot be applied directly, the trustee, still wishing to develop the domestic load, would next have to inquire " What is the load factor of the domestic load ? "

On page 586 a 40 % load factor for domestic supply on its peak and a diversity of 1·6 (this is not small, as is realized when it is expressed as only a 62·5 % overlap) is assumed. This represents a load factor of 64 % on the system peak, as compared with the average load factor of 50 % given in Table 1 for houses not using their cookers in the winter.

In col. 2 of page 586 the author takes a peak load of 23 652 kW and assumes that the power and private-lighting peaks coincide with it absolutely. He then assumes that the domestic peak has no diversity with the system peak, and calculates a load factor. If the diversity factor of 1·6 applies in one case, why not in the other ? If that factor is applied, the load factor of the domestic load on its peak is found to be 31 %, which is a more reasonable value.

* *Journal I.E.E.*, 1933, vol. 72, p. 359, Table E.

Regarding the subject of load factors, one might justifiably complain of the misleading impression created in Table 3. On the face of it a 41·3 % load factor looks remarkably good, but if the load factor is calculated on sales this value is reduced to 33·8 %, which is a clearer indication of the habits of the consumers.

Armed with this information the trustee can now ask: " Is the general case quoted on page 576 a proof that the tariffs proposed are feasible ? " The first point which would be noted is the annual consumption. This is low for complete electrification, but very high when compared with the figures given in Table 7. Management charges, rates, etc., have again been allocated on the peak-responsibility basis. Coal adjustment has been omitted. The service and meter apparently bear no interest or repair charges, for they cannot, one would think, be charged at so much per kW. Losses for Hull are 16 %, whilst 10 % has been assumed. Then there is the question of load factor: from what has been said, a figure of more than 50 % on the system peak cannot be assumed, and either one or both of the author's assumptions (*a*) and (*b*) must be wrong. Take (*b*) as correct: then to sell 3 504 units the demand on the domestic peak is 1·28 kW and on the system peak 0·8 kW. Thus the costs on a peak responsibility basis are:—

£9 10s. × 0·8	1 830d.
3 504 units at 0·225 + coal at 0·03d.* + 16 % losses	1 030d.
	2 860d.
Revenue, as before	2 292d.
Loss	568d.
Annual charge on service and meter (average of prepayment and quarterly), say ..	150d.
Total loss	718d.

There is one further question which the trustee might ask: " What is the possible effect of regular heating ? " The follow-on rate of ½d. falling to ⅓d. is low enough to make regular space-heating by electricity as cheap as by a coal fire in the average house. Has the author considered the possibility of this, bearing in mind that the maximum load factor of the heating load is fixed by the number of hours per year, from, say, 8 a.m. to 11 p.m. (with a long daily break in most poorer houses), during which the temperature is below, say, 60° F. ? Suppose that half his consumers decided to adopt space heating; then, judged by my own flat, the system peak would increase by at least 90 000 kW. As a trustee of the nation's money, would the author feel justified in putting down mains to cope with this load and in increasing his demand on the C.E.B. to this extent at the present selling prices ?

After considering the above questions I am afraid that

* For 1938 this appears to have every likelihood of being at least 0·06d.

our impartial trustee would decide that the general case for domestic electrification is not proven, and would inquire why the supply industry has not spent more money in obtaining comprehensive statistics on the incidence of load and on research into the question of allocating costs.

Mr. G. H. Swingler (South Africa) (*communicated*): I am at one with Mr. Waite in my dislike of imposing restrictions on the use of appliances if this can possibly be avoided, but I imagine that his objection to restrictions on water-heating service might possibly be influenced to some extent by the realization that in any case there is not likely to be any considerable demand for that service in Hull in the immediate future, if at all. I am satisfied that there is a very large field for the development of a water-heating service in Cape Town if this service can be given at ¼d. per unit, but electrical energy cannot economically be sold at that price if the corresponding load comes on simultaneously with our peak load. Admittedly, the Reyvaux switches do not ensure with any certainty that the load of some of the water-heating apparatus will not come on the peak, but they at any rate do introduce a very considerable diversity, which is of material assistance in improving the load factor. Neither of the authors of the papers, when discussing the factors bearing on the popularity of the use of electricity for domestic purposes, touch on the influence which climatic conditions have in that direction. In a climate such as Durban, where the average temperature for the whole year corresponds closely to the average for the three hottest months of the year in Cape Town, there is a spontaneous tendency on the part of housewives to accept any means which will lead to more convenient and more comfortable ways of carrying out household duties than previously they had perforce to adopt. This influence of climatic conditions applies particularly in the case of water heating, since in Durban, for example, the amount of electrical energy used for raising the water to the desired temperature is very much less (because of the more uniform and higher average inlet temperature of the water) than in Cape Town, where during most of the year the inlet temperature is probably of the order of 20 deg. F. lower than in Durban.

Our experience in Cape Town, where there is a European population of 165 000 and a consumption (excluding railway electrification) for industrial purposes of approximately 53 million units per annum, and where during the past 7 years the annual sales of electrical energy have increased from 65 million to 192 million units, almost entirely owing to the success of the hire-purchase scheme in promoting the extensive use of electricity for domestic purposes, is that the annual load factor, instead of being lowered because of the domestic load, as those in some undertakings seem to fear it will, remains steady at about 43 % to 46 %. The consumption on the "all-in" domestic tariff rate by 36 000 consumers now amounts to 115 million units per annum (or 3 190 units per domestic consumer) and is still rapidly rising.

During the past 7 years of the working of the Council's hire-purchase scheme we have sold 16 314 cooking ranges with a loading of not less than 3·5 kW each, of which approximately 23 % are of British make and the remainder, with insignificant exceptions, are of American or Canadian make. The latter are more popular, to a great extent, I think, because their general appearance appeals more to the prospective purchaser than the typical British-made ranges that have been offered for sale in the past. I would also suggest, as a possible reason for the greater popularity of American and Canadian cookers, that most housewives who adopt electric cooking in this country are "kitchen proud" in the same sort of way as those in Canada and America have been for many years, so that there may be a greater affinity in likes and dislikes of that kind between those countries and South Africa.

Table A

Loading	Retail values	Total sales (7 years)	Percentage of total sales
Under 3 500 watts	Up to £17	171	1·05
3 500 watts and over	£10–£15	199	1·22
	£15–£20	3 005	18·42
	£20–£25	4 446	27·25
	£25–£30	3 418	20·95
	£30–£35	2 617	16·04
	£35–£40	1 278	7·83
	£40–£45	784	4·80
	£45–£51	308	1·90
	£51 and over	55	0·34
Heavy duty	£51 and over	33	0·20
		16 314	100·00

The pedestal type of range, with the oven below the boiling-plates, is more popular here than the table-top type—60 of the former have been sold under the hire-purchase scheme as against 40 of the latter. The extra cost of the table-top type influences this division.

Table B

	Country of origin		
	Canada and U.S.A.	Great Britain	Total
No. of ranges serviced ..	2 764	1 405	4 169
Location and type of fault:—			
High-speed elements ..	668	13	681
Boiling-plates	973	851	1 824
Oven and hot-cupboard elements	136	38	174
Boiling-plate, top only	216	—	216
Thermometers	105	181	286
3-heat switches.. ..	271	176	447
Door springs	437	47	484

So far as price is concerned, Table A shows that ranges selling at between £20 and £24 are the most favoured by those taking advantage of the Council's hire-purchase

system, and they are followed in order of preference by the £25 to £29 and £15 to £19 classes.

The British-made ranges which we have handled are more robustly made than the others, but, as can be seen from Table B, setting out faults which were attended to during the first 2 years of the lives of a large number of ranges supplied through the Council's hire-purchase scheme, the former have very little, if any, advantage over the latter from the standpoint of service needs. There is undoubtedly a strong desire on the part of a very large number of people in South Africa to "buy British," but if much progress in sales of British-made ranges is to be made in this country, where there is such keen competition from manufacturers in all parts of the world, British makers must realize and act on the fact that what might be readily acceptable to a prospective purchaser in England is quite likely to be exceedingly difficult to sell here.

Two years ago I had personal experience of the way in which competition is met in one place in England, when a short time after having seen one of the latest models of a high-class Canadian range in the showrooms of a well-known electricity supply company I tried to make arrangements to hire one. To my surprise I was informed that in the meantime they had discontinued stocking that make and had only one make—a typical English range—from which I could make my selection. Inquiries showed that a certain large manufacturing firm in England has a holding not only in the supply company but also in a company manufacturing electric ranges in England. The consumers connected to that company's system accordingly can hire only that make of range which a firm that is not even actively interested in range manufacture consider they should have. Where keen competition is met with from other sources, for example from gas in the district to which I am referring, action of this kind is very wrong. The public should be allowed to select from a reasonable number of makes; and I

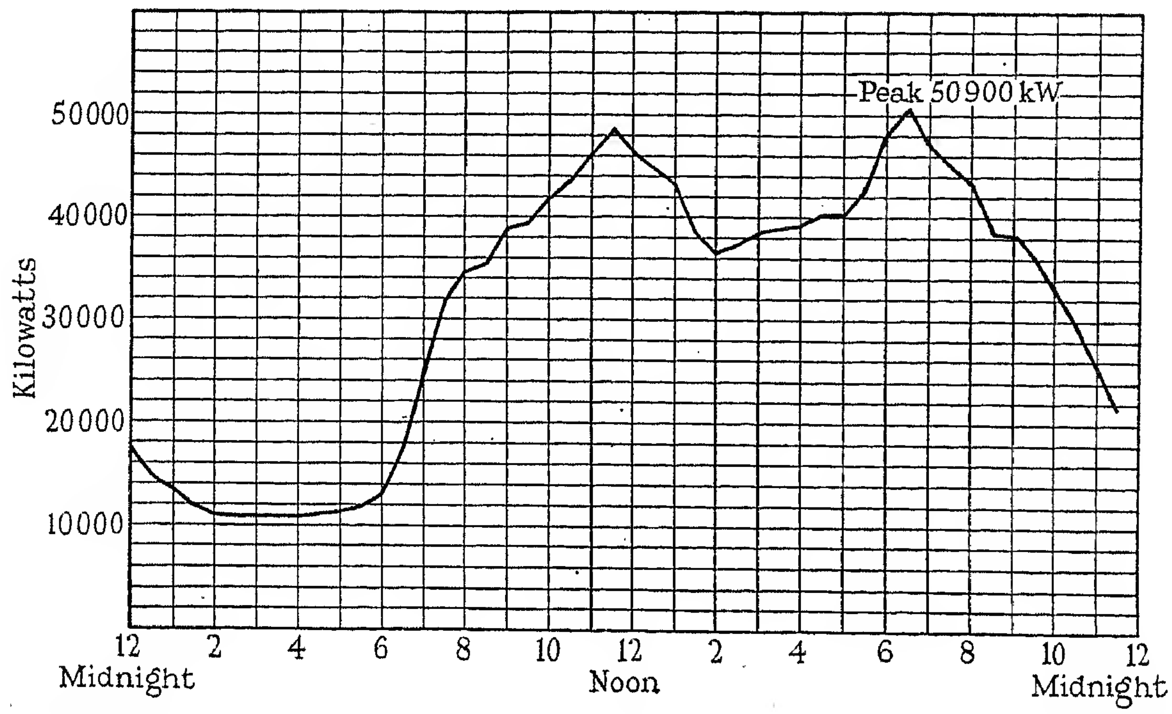

Fig. D.—Demand curve of the City of Cape Town supply system, Tuesday, 13th July, 1937.

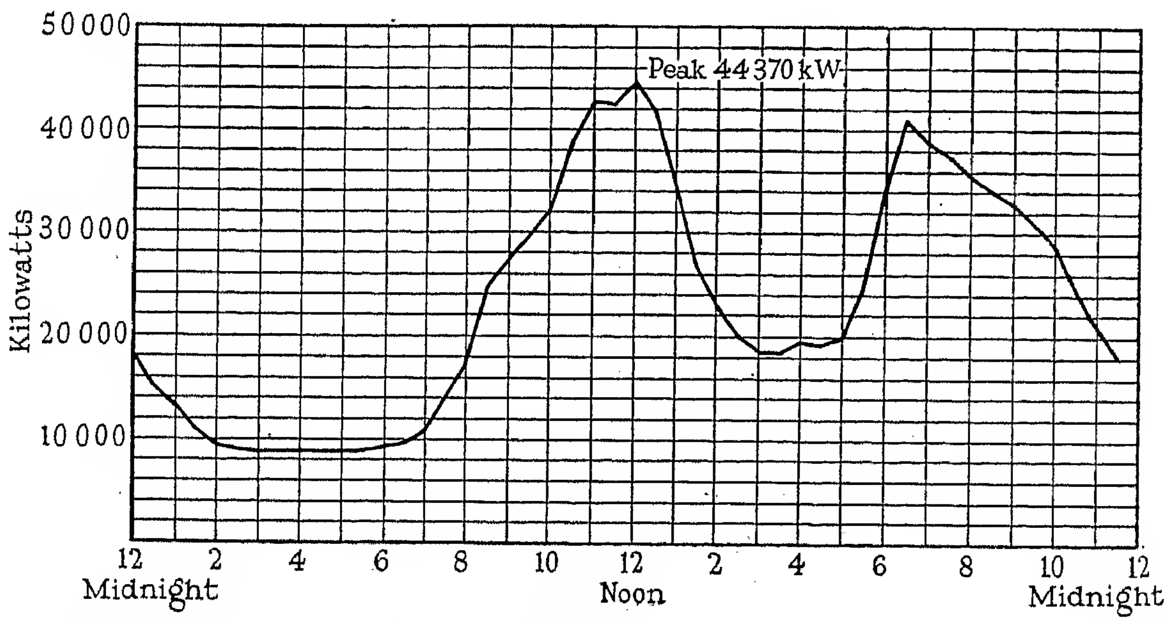

Fig. E.—Demand curve of the City of Cape Town supply system, Sunday, 25th July, 1937.

submit that it would be to the good of all concerned if, when the manufacturing associates of a supply company is not making an attractive range, the company help to bring them out of the rut by dealing in more attractive ones.

The question whether a hire or a hire-puchase method of introducing electrical appliances into the home is to be preferred by an electricity undertaking is one which is governed largely by the purchasing power of the community served. Where this is so low that for the appliances to be purchased at all the hire-purchase terms must be spread over a very lengthy period, the hire system will, I think, obviously be the more likely to produce the desired results. Where, however, the purchasing power of the community is relatively high, as in most of the larger centres in South Africa, the hire-purchase system is pre-eminently the better from the point of view particularly of the electricity undertaking, which is relieved of responsibility for maintenance after the expiration of the repayment period and to that extent is rendered freer to direct its activities towards extending its business. The undertaking automatically avoids difficulties inherent in hirers becoming dissatisfied with a range when after a few years it becomes out of date, and greater interest generally is likely to be taken in an appliance which the consumer is prepared to own. Moreover, a consumer who has *purchased* his appliance is much more likely to be for all time a consumer of electricity than the one who has been a consumer merely through the fact of his *hiring* an appliance, if only for the reason that he can at any time terminate the hire and change to the use of some other means of heating and cooking without suffering any financial disability such as would apply to one who had spent money on his own electrical equipment.

Fig. D shows a load curve for the Cape Town Council's undertaking on the day of the highest demand during 1937, and Fig. E a similar load curve for a typical Sunday during the winter months. The morning load of the last-mentioned curve is made up almost entirely of the domestic load for cooking and water heating.

Mr. W. E. Warrilow (*communicated*): It does not follow that because the electric cooker has achieved the distinction of being discussed at a meeting of The Institution it is to be regarded as an engineering product. Actually, the electric cooker of to-day is nothing more than a coal or gas oven, fitted with electric heating elements. Every electrical engineer must deplore the fact that all attempts at commercializing a specially designed electric cooker have hitherto met with failure; I may quote, as notable instances, A. F. Berry's "Tricity" polished tin "biscuit box" oven, and Napier Prentice's "diving bell" oven, both of which, in a strictly thermal sense, were highly efficient. It is not the fault of the electrical engineer that he has completely failed to break down the ingrained prejudices of countless generations of cooks—male and female—the former especially, and the latter to a lesser degree.

Mr. Humphreys, in his historical review of boiling-plates on page 576, omits to refer to two pioneers whose early work did at least help forward the electric-cooker movement. One of these was A. F. Berry, whose boiling-plate was a transformer with a short-circuited secondary: it is being revived to-day, after some 25 years, in the form employing a resistor secondary raised to a red heat. The other pioneer was the late C. Orme Bastian, who was the first to introduce a closely wound element of nickel-chrome; each turn was in direct contact with its neighbour, but owing to the thin film of oxide on the surface of the wire the current followed the path of each convolution, and in this way an exceptionally high temperature was obtained. Bastian was limited in his choice of refractories, and was compelled to use quartz tubes to enclose the elements.

Mr. Humphreys does not mention electric kettles; I realize that they are not an integral part of a domestic electric cooker, but they are becoming more and more important in the matter of the quick boiling of water in the kitchen. In my own house we draw water to be boiled from the hot tap, allowing the water to run until it is very hot (about 120° F.), and in a 3-pint kettle with totally immersed element loaded to 1 500 W that water is boiled in exactly 4 minutes, a much shorter time than would be taken by any boiling-plate similarly loaded.

Turning to Mr. Waite's paper, I should like to know—in respect of boiling-plates and grills working at a high temperature—the number of faults he has met with which are due to the burning-through of the element wire close to one of the terminals. I should like to quote my own experience. When we built our own all-electric house 9 years ago, we installed a family-type cooker with a maximum loading of 7 kW; the boiling-plates were of the enclosed type, with moulded asbestos covers. This cooker was in continuous service for 7 years without any failure, but at the end of that period one boiling-plate burnt out; last year, after 8 years' service, the bottom element of the oven followed suit. Twelve months ago we decided to install in addition a table-type cooker with oven having single-heat control, and grill and boiling-plate with 3-heat control. It is with this latter that we have had the terminal trouble to which I have above referred. The element wire, which is always at a red heat, is clamped between brass washers, and on the first occasion when only half the grill functioned I decided to investigate the matter for myself rather than call in the local electrician. I then found that, at the point at which the wire entered the washer, local heating had been set up, and this had steadily built up a temperature corresponding to a "hot spot," which had ultimately burned through the wire. In 12 months' service this cooker failed three times in this way, at exactly the same spot, and always at the same terminal. Some idea of the heat generated at this point may be gathered from the fact that the washers crumbled when the terminal was unscrewed. I suggested to the makers that they might use washers of metal having an expansion coefficient equal to that of the element wire. I gathered that the same defect was causing repeated failures of this type of cooker, occasioning considerable inconvenience to users and bringing the type into disfavour. This experience emphasizes that every point in the connections of an electric cooker should be made as far as possible immune from breakdown, particularly if the remedy is quite a simple one.

[The authors' replies to this discussion will be found on page 615.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 24TH JANUARY, 1938

Mr. R. H. Rawll: Dealing first with the paper by Mr. Humphreys, the author in referring to the comparatively low insulation resistance of the embedded-type of plate gives a figure of 60 000 ohms, while later in the paper a figure of 250 000 ohms is given. It is not clear whether this latter figure applies to the same type of refractory. I am fully in agreement with the author that a simmering heat is required on boiling-plates, as with the normal 3-heat type of control such operations as jam-making are sometimes difficult. Perhaps the author will indicate whether he agrees with my own contention that the life of a cooker produced to-day is considerably longer than of one manufactured only a few years ago.

Turning to the paper by Mr. Waite, it is refreshing to see his statement that usually a cooker hire scheme has to be subsidized. Such a policy is justified considering the very large number of potential cooking consumers there are, and the duty of an undertaking to give service to the whole community throughout the area of supply. The main value of the paper is its frank examination of the economics of cooker hire schemes. A large number of supply engineers to-day do not know how much their cooker hire schemes are costing them.

Maintenance costs should first be ascertained, and these, together with the cost of the equipment, should be balanced by the hire rentals received. If the two are not equal (and very few cooker hire schemes show such a balance) the remaining sum can only be recovered from the profits on the sale of units. My own view is that since a very large number of units result from the installation of electric cookers, such a policy is justified provided the hire charge is not reduced below a figure where it is competitive with that applying to gas cookers of equivalent service.

I consider, therefore, that it is very desirable for every supply undertaking to determine exactly the amount that hire schemes are costing them. I should be obliged if the author would state what exactly is covered by the item of £2 12s. 11d. described as " other fixed charges " in Table 2.

In his comments on Table 5 the author gives some interesting figures for the load factors of various classes of supply. I presume that these are the load factors prevailing at the time of the undertaking's maximum load, because otherwise the resulting calculations which determine the load factor of the domestic supplies will not be correct.

As regards disconnection of cookers in the Birmingham Undertaking, I find that the number of dissatisfied cooking consumers is less than 0·5 % per annum of the total net cookers connected. This is a very good indication of the service that has been done by lady demonstrators.

I am interested to see from Table 10 that although the total number of cookers has increased, fewer maintenance calls are being made; this is good evidence that cooker design has been improved.

Finally, I cannot agree with the author that at the present time 20 years is the economical life for normal depreciation of a cooker. Most of us have not had sufficient experience of cookers to arrive at this conclusion, and it would be interesting to know on what grounds such an estimate is put forward.

Miss M. Hooper: The kitchen in a modern house is very small, and an electric cooker offers the maximum cooking space for the total space occupied. I should like to ask the manufacturers of electric cookers to issue more detailed instructions on how to use and clean them. As Mr. Waite says, the electric cooker is a new type of household tool which requires a slightly different technique from its predecessors.

With regard to maintenance costs, I think it will be possible to improve even upon the low average figure of 14s. 1d., quoted in Table 11 of Mr. Waite's paper, when the average housewife knows how to take care of and properly use her electric cooker.

I should like to see electric cookers installed in large quantities on new housing estates. Some means of cooking has to be installed, and I do not see why electric cookers should not be adopted as a matter of course.

I wish to stress the point that it is not the cooker having the lowest initial cost that the consumers want to hire or hire-purchase. They want a cooker that is substantially built, and they are even willing to pay 1s. or 2s. extra per quarter for a brightly coloured cooker to match the kitchen. I suggest, therefore, that supply authorities who choose their cookers solely on a price basis are not going to be an asset to the electrical industry.

As regards switching arrangements, automatic thermostatic control is now available, facilitating the use of the oven, preventing overheating, and economizing in energy consumption. This type of control can be greatly exploited to-day, to make electric cooking even more popular.

Electric cookers might with advantage be made simpler to use, and there should be greater simplicity in the form of domestic tariffs. Many consumers and householders seem to think that tariffs are for the supply authority only to understand. It is difficult to explain a complicated tariff to the housewives in country districts.

Mr. T. A. G. Margary: I am sorry that Mr. Humphreys has not found it possible in his paper to deal with the design of cookers from the point of view of maintenance. To the supply industry the ease with which a cooker can be taken down, cleaned, and put together again, is vital. Housewives will not have apparatus which looks "secondhand," and before a cooker which has been used by one consumer can be passed on to another it has to be stripped, cleaned, polished, and made to look perfectly new.

The top plate of the modern cooker is, I suppose, as satisfactory as it is possible to make one with the materials that are to hand. Its life, however, is nowhere near as long as I hope it will eventually be, and were it not for the fact that the makers give a 2-year guarantee of their boiling-plates the cost of maintenance would be prohibitive.

The oven, on the other hand, is not so good as it was some years ago. One of the reasons for this is the present fashion of having the switches down the side of the cooker; as the dimensions of the body of the cooker can-

not exceed those of the top plate, it has been necessary to reduce the width of the oven.

I consider the most satisfactory type of oven to be that shown in Fig. 4 of the paper by Mr. Humphreys, with the elements at the side and covered with a casing open top and bottom, which acts as a chimney and causes rapid circulation of the hot air in the oven. Unless the air is circulated, the joint being cooked is not swept with hot air, and to ensure cooking in reasonable time the temperature of the oven has to be kept unnecessarily high.

With the type of oven in use to-day, the amount of metal and enamel which has to be heated is considerably greater than with earlier types, and an excessive amount of electrical energy is wasted in heating up this mass. It is all very well to talk of cooking by residual heat, but in the ordinary way this heat cannot be taken advantage of, with the consequence that it is wasted. The electrical business has been built up on a basis of efficiency, and even with electricity as cheap as it is to-day its most efficient use is of vital importance.

I cannot agree with Mr. Waite's contention that quick boiling is not of vital importance. The electric cooker is so satisfactory to-day that the only point our competitors can pick upon is the time it takes to boil a kettle by means of electricity. This argument has been used to the full, and has only been overcome by the use of the latest heavily-loaded boiling-plates.

Prof. W. Cramp: Further improvements in the design of electric cookers will depend not so much upon changes in principle as upon perfection of detail. The following seem to me to be the chief points requiring attention:—

(1) Both main and circuit switches are at present much too noisy; often the turning of a switch is heard throughout the house. Since nearly all cookers are now used upon alternating current, there is no reason why the switch should not operate quietly. It need not be of the quick-break type, and the break may be quite short: a few thousandths of an inch is sufficient.

(2) Most cookers have too little clearance between the bottom of the oven and the floor. The space should be sufficient to enable adequate sweeping to be carried out, and to avoid kneeling to inspect the oven.

(3) The present system of lagging is not satisfactory, and I can confirm Mr. Humphreys's remarks concerning the use of aluminium foil. Slag wool and glass silk are undesirable. The former is particularly dusty, and it gradually breaks up; after the cooker has been moved once or twice, it tends to settle down into a hard mass and to lose its heat-insulating properties. I have found five sheets of crinkled aluminium around a hot-water tank as good an insulating agent as slag wool can provide, besides being clean and easily removed. The cost is only a few shillings for the material, and the labour in applying is negligible. Thicker lagging is undesirable, because of the space lost, which daily becomes more valuable in modern houses and flats.

(4) Mr. Humphreys's investigation of the distribution of temperature in the oven is important, and his suggestion of a definition of " heating condition " is work for the British Standards Institution. Once this quantity has been defined, there will be an opportunity for good research work by a technical college where domestic science forms part of the curriculum. Even when the heat indicator is calibrated in terms of this condition, however, there will still be a margin of error due to individual idiosyncrasy. This is because, though the heat transfer may be known, two users will hardly ever have similar material in the same state when placed in the oven.

(5) The suggestion on page 573 of Mr. Humphreys's paper, that the life of a cooker is from 5 to 9 years only, contrasts sharply with the views of Mr. Waite. If Mr. Humphreys is correct, the American practice of making the apparatus light and cheap, so that it may be replaced at the end of 9 years, appears to be right, and it is possible that improvements will be sufficiently rapid to make this short life desirable.

(6) High-voltage exposed-type boiling-plates are, in my view, exceedingly dangerous, and should be forbidden by the regulations.

Mr. Humphreys thinks that the heat transmission from any boiling-plate is almost entirely radiant. If this is the case, why is it impossible to buy saucepans with black bottoms for electric cookers?

(7) His Tables 2 and 3 are excellent evidence as to the fallacy involved in the low-voltage exposed-resistor boiling-plate, and of the great importance of the absorption coefficient. It will be difficult to convince housewives on this point, but the publication of such figures, followed up by demonstrations in Corporation showrooms, should teach the housewife to discount the effect of the visible red-hot element, and to accept the test figures.

Mrs. A. Williams: The production of a cooker which is electrically perfect should not be marred by rough shelves and grill tins which stick every time they are taken out. These points mean more to the average housewife than the question of quick boiling, a feature which in my experience is the cause of fewer complaints per year than any other.

With regard to Mr. Margary's remarks about the cooking of a joint, we try very hard to persuade housewives that meat must be given a high temperature for only a very short time, and then a low one.

As regards the height of the cooker above the floor, unfortunately housewives differ in size, and if the base of the cooker is arranged 1 ft. from the floor a small housewife will not be able to reach the top. There is not room in the modern kitchen to install a table-model cooker.

Mr. R. S. Gilling: I suggest that from the practical point of view an ideal method of oven heating would be with the elements clamped to the oven interior. This eliminates the element chamber and, since the whole oven is the heater, gives a low density of loading. This means lower temperature of the elements, and possibly the elimination of crazing of the enamel. Heating with this arrangement is by convection and conduction, but if radiant heat is required thin strip heaters can be plugged-in at the top of the oven.

I should also like to stress the advantage of sheathed-wire boiling-plates from the point of view of heat-transfer. On working out the efficiencies for the various plates given in Table 2 I find that, for the various types of utensils used, the efficiency of the sheathed-wire plate only varies between 52 % and 60 %, while

that of the cast-iron embedded plate varies between 39 % and 59 %. This shows the great advantage of the sheathed-wire plate in that it gives excellent efficiencies with any type of utensil.

Mr. H. W. Wilson: Too much stress appears to be laid on the question of the design of the oven of the electric cooker, and not enough on the design of the boiling-plates. In the average household, particularly where there are children, the boiled meal is far more important than the roast or the grilled. More boiling-plates should be provided, and a simmering control is essential. At the present time the majority of cookers in this country are obtained on simple hire, and it is false economy to supply these without efficient means for simmering. In at least one large undertaking the cookers for hire are sent out with only two boiling-plates, and no simmering control is provided, with the result that many people install a gas-ring in order to supplement the boiling-plates and to allow better facilities for boiling small quantities of water and milk, or for making sauces.

I am interested in Mr. Humphreys's suggestion that a glass door would be an advantage. It appears to be necessary, particularly in the early stages, to observe the joint when roasting, and the opening of the oven door results in a fall in temperature, in consequence of which a certain amount of supervision is required until normal temperature has been attained once more.

I disagree with those who advocate that certain cooking operations should be carried out by means of supplementary devices. A cooker should be capable of carrying out all cooking operations, and an up-to-date electric cooker equipped with at least three boiling-plates and an efficient simmering control, together with a plug for an electric kettle, would adequately fulfil all of these requirements.

Mr. E. T. F. Onley: Dealing first with the paper by Mr. Humphreys, I should like to suggest that the size of the hot-cupboards on small cookers be increased slightly. Our own cooker is supposed to be suitable for cooking for five people, but it is most difficult to arrange a dish, five plates, two vegetable dishes, a sauce boat, and a gravy tureen in the hot-cupboard for warming purposes, owing to the position of the support for the grilling pan: an extra inch on the height of the cupboard would make all the difference between a very tight squeeze and an easy fit. Further, although the oven easily accommodates a 16-lb. turkey, the hot-cupboard is not large enough to permit the warming of a suitable dish.

I would also suggest that when the main switch for the cooker is fitted with a kettle socket the "on" and "off" positions for the latter, as well as those for the cooker, should be marked on the cover. At my home the cooker switch is closed by lifting the handle, while to switch on the kettle another switch in the same case has to be depressed; the two switches certainly follow the usual convention for the particular types used, but when they are both in the same case their operation is sometimes confusing to an outsider who may be called in to help when the housewife is unwell.

Turning to Mr. Waite's paper, I should like to suggest two points which would probably lead to a slight reduction in cooker maintenance costs. First, a pilot light fitted to the main switch would reduce the possibility of the cooker being left on, with consequent overheating of boiling-plates, etc., as the light would be easily noticed, especially at night-time. Secondly, greater attention should be paid to the jigging and assembly of the plugs and sockets on plug-in grill-boilers and boiling-plates which are supposed to be removable for cleaning purposes, as the forcing which so often seems to be necessary to remove one of these parts leads to a danger of breakage of the porcelain shields around the sockets.

Mr. L. F. Whyman: Mr. Humphreys mentions that with thermostatically-controlled cookers the results are improved by reducing the amount of lagging. I have seen this demonstrated in a cooker made from what were, in effect, two biscuit tins, one inside the other, with elements between. The results were very satisfactory, and the running cost was little more than that of a lagged cooker.

I note that the performance of a thermostat is affected by its position in the oven; how does the weight and the size of the operating tube affect its operation?

Cooker construction could easily be simplified by sliding parts together instead of using screws. This method would also reduce reconditioning costs.

Mr. R. Dean: In my opinion aluminium or cast-iron utensils provided with flat bases should be made available through the hire charge of electric-cooker hire schemes. Such utensils not only reduce energy consumption, but, by providing closer contact where solid-type boiling-plates are in use, absorb the heat much more effectively and thus eliminate hot spots. In this way they materially lengthen the life of the boiling-plates.

With regard to transformer-operated plates, where these are being installed on systems of non-standard voltage the transformers should be provided with tappings at the outset, so as to enable them to be used at a later date on the standard voltage.

On cookers provided with a 1 000-watt boiling-plate, simmering can be done in the low-heat position of 250 watts. This is a strong point in favour of fitting a 1 000-watt boiling-plate on cookers as an alternative to the other boiling-plates.

Referring to the fixed-charge portion of the rateable-value tariff, I consider that it is psychologically better to divide this charge into four equal quarterly payments than to charge one-third for each winter quarter and one-sixth for each summer quarter. Where the latter method is adopted, accounts for the winter quarter appear unduly heavy, owing to the combined effects of increased energy consumption and the heavier standing charge. It is found in practice that consumers prefer a system under which their electricity accounts for the four quarters are more even, and as winter is a period of heavy domestic bills this method no doubt reduces the number of complaints from consumers.

[The authors' replies to this discussion will be found on page 615.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 14TH FEBRUARY, 1938

Mr. P. Ward: I am still not sure that from the maintenance point of view vitreous enamelling is going to be the best finish for cookers let out on hire, though it certainly is for selling purposes.

With regard to Mr. Humphreys's comments on dimensions and loadings (page 568), the ovens with the lowest loadings are, I think, generally those of the manufacturers whose designers have kept most in mind the proper function of the oven. Where high loadings are employed the designers have built their ovens for convenience and then put in heating elements of sufficient capacity to maintain a cooking temperature on low heat.

Ventilation troubles did not show themselves until welded interiors were introduced. The problem is really one of getting surplus moisture clear of the cooker itself before it can condense. On page 569 the author says that it is of little importance where condensation takes place. Nevertheless, the housewife will not agree that it does not matter if condensation has to be wiped up beneath the cooker.

In these days of cheap electricity, lagging is not of such importance as formerly from an efficiency or running-cost point of view, but it must be such that the oven temperature can be held stable in the draught of an average small kitchenette, where the cooker is frequently close to an outer door.

A standard scale to indicate the heat condition of ovens is necessary, if any scale at all is to be used. Many consumers, however, do not use their thermometers as such, but only as indicators. On urban networks, where the voltage regulation is usually good, many prefer to work on a time basis, as we used to do entirely years ago. In rural areas where good regulation may not be so general, some guide to the heat condition is almost essential.

I am not at all convinced that thermostats are necessary, or even desirable, from a cooking point of view. It is generally overlooked that a large proportion of domestic cooking is done best, not in a steady oven, but in one with a drooping temperature. The gas interests were compelled to use a thermostat to get results such as we could get with ordinary 3-heat control, and they cleverly made a virtue of necessity. Nevertheless, it is still easy to convince the public that there is no necessity for thermostats. From a distribution point of view, it is claimed that a thermostat maintains a steady temperature on fluctuating voltages, e.g. in rural areas. I agree that it has an advantage there, but it will not solve the whole problem, as the boiling-plate and grill are still left to look after themselves, and the consumer would still be dissatisfied with their erratic performance. For commercial baking purposes the thermostat is a distinct benefit, both in regard to temperature control and also saving of energy.

It should be possible by means of thermostatic control to produce an oven of low thermal capacity and high loading, which would have a shorter initial heating period than present cookers, and a lower production cost. Its running cost would probably be higher, but that, within reason, would not matter. Such a cooker would be totally different in principle from present cookers and would have to be specially designed for the purpose.

With regard to boiling-plates, I have always believed in a radiant plate for domestic purposes, for two reasons—one psychological, and the other the fact that with a radiant plate any pan can be used. I have, however, been using solid plates for many years, and with the improvements made in the last 3 or 4 years I consider that they are still the best all-round proposition. I should like to use the sheathed-wire type of plate, but makers have not yet produced a satisfactory and easily-cleaned means of mounting it, its first cost is still too great, and it offers no reduction in maintenance costs.

Present-day boiling-plate loadings are satisfactory for cooking purposes. Plates with high loadings only result in the burning of foods, and with present loadings simmering does not present difficulty. When simmering is in progress there is generally more than one pan in use and each pan need only cover sufficient area to keep it on the simmer, leaving very little plate area to dissipate heat to air. Rectangular plates have an advantage under these conditions, as the plate corners penetrate farther into the centre of the pan.

Turning to Mr. Waite's paper, I should like to know at what rate the slot-meters are generally calibrated to cover the fixed charge in the Hull area. Are the calibration adjustments not found to be too frequent?

The fact that the bulk of the future cooking load will come from working-class houses raises the question of possible cheaper designs of cookers, and also of the class of demonstration necessary. Formerly the cooking load came from the more well-to-do consumers, and from "cranks."

While we do not provide pans with hired cookers, we are now doing so with cookers supplied on easy-purchase terms, as an additional inducement to purchase; but we do not include a kettle for use on boiling-plates. We encourage the use of electric kettles.

It is better for a supply authority to confine its purchases to one make of cooker and to make radical changes as seldom as possible; otherwise obsolescence costs are high. We have not had to scrap any cookers before they have redeemed themselves, and have in fact many which have remained in service beyond the redemption period. I would emphasize the importance of taking the manufacturer's standard article which most nearly meets consumers' requirements. If this had been done all along, prices would have fallen earlier than they did, and development and research by manufacturers would not have been any less keen.

While I agree that good results can be obtained with any disposition of oven elements, side heating allows a greater amount of work in a given cubic capacity and makes it more easy to keep the oven clean, by reducing splashing. This has an effect on maintenance costs.

Quick-boiling plates are not generally necessary, and they result in burning of foods. For quick boiling of water it is preferable to use self-contained kettles.

I should like to know what floating stocks of (*a*) new cookers, (*b*) reconditioned cookers or cookers awaiting reconditioning, the author has normally to carry.

Mr. F. E. Heppenstall: I should like to refer to the use of cookers made of pressed steel. One of these with

which I am acquainted is a very successful appliance: it has aluminium-foil lagging and an 800-watt element, and it heats up very quickly. One of its great advantages is that there is no waste heat left over after the cooking is finished.

Many manufacturers do not give sufficient attention to the earthing of cookers, a matter which is a frequent cause of shocks. I have known an element in a cooker reach a resistance to earth of 30 ohms after a year's use.

I should be glad if Mr. Humphreys could give actual figures for the life of boiling-plates.

When a boiling-plate is wet its insulation resistance is low, and switching-on may cause a considerable current to flow to earth. Where (as in rural areas) an earth-leakage circuit-breaker is installed this will cause tripping and unnecessary maintenance work. I should be glad to know whether Mr. Humphreys has any further information on this subject.

With regard to flat-bottomed utensils, I think the trouble is that consumers will not or cannot pay for these.

Turning to Mr. Waite's paper, I have some figures taken in Newcastle in 1934 for cooking only, from a number of recorder charts. These show an average of 0·146 kW per cooker on the undertaking peak and 0·57 kW per cooker on the morning peak. The average consumption for cooking only was 747 units for 4-room houses, the rateable value being £17.

Table 2 shows a surplus, assuming that the consumers in question have their own cookers. If these cookers are hired, however, at rates which are presumably unecomic, the position is not quite so favourable. Basing the costs on a capital of £12 per cooker for a 10-year life, and assuming interest at 4 %, the capital charges are £1 9s. 6d., and allowing 14s. for maintenance the total annual cost is £2 3s. 6d. If a 20-year life is assumed, the capital charges are 17s. 9d. and the total annual cost £1 11s. 9d. From the figures in Table 1 I find that the surplus is 7s. per consumer, and if the hire charges amount to £1 per annum there is only £1 7s. available towards the annual cost of the cookers, which are therefore apparently subsidized out of receipts from other consumers. Mr. Waite does not give his hire charges for cookers, and I think it would be interesting if these were included in the paper.

The great advantage of cookers is, however, that they promote the use of other appliances, a fact which is worth quite a lot to an undertaking from an advertising point of view.

The art of grilling is not known very well in this country, and owing to the advantages of electric grillers it would pay well to develop it.

Mr. C. G. Whibley: My comments on the paper by Mr. Humphreys are based on information gained in the development of a consumers' engineer's department of an Australian undertaking, where electric cookers were purchased by consumers either for cash or on the basis of a deposit of 20 % and monthly payments over 2 years.

The suggestion that the heat indicator should be calibrated with standard heating-condition numbers in place of degrees Fahrenheit is valuable. It would eliminate the present impression of many consumers that the operation of an electric cooker requires an accurate knowledge of cooking-temperature conditions, and that one has to be particularly trained to use an electric cooker.

The top-and-bottom-heated oven was the most popular among the consumers of the undertaking to which I have referred. The use of thermostatically-controlled ovens was limited, and consumers' reports on their operation indicated that they were unsatisfactory. The thermostats were approximately in the position shown in Fig. 6, and so Mr. Humphreys has clearly indicated the reason for the consumers' dissatisfaction. Manufacturers would assist supply authorities materially in promoting the use of electric cookers by ensuring that adequate technical information is available, so that the staff may be able to answer at once any questions that may be asked.

Sheathed-wire boiling-plates were the most popular, and their psychological appeal may have facilitated sales. The fact that up to 25s. each was asked for machined-bottomed saucepans, and that these were recommended for cookers with solid boiling-plates, undoubtedly discouraged the purchase of these cookers. Further, the efficiency of the machined-bottomed pan is dependent upon the cleanness of the boiling-plate surface, a matter over which manufacturers have no control.

Electric grilling is widely used in Australia, and justifies the provision of a separate grill. With top-and-bottom-heated ovens the top element is used for grilling; but the average top element is unsuitable for grilling for a small family, because the alternate arrangement of the two halves of the element prevents the use of the medium-heat position for small grills. Seeing that the top-oven element is only used for oven-preheating, practice having shown that it is not essential for browning, I suggest that the half of the element used on the medium-heat position should be concentrated in the centre.

I should like the author to state the efficiency of a griller-boiler plate as a boiler; considerable losses occur in the average 2-boiling-plate cooker owing to its use in this way.

It is the practice of supply authorities in Great Britain and in Australia to encourage the use of immersion heating devices, and cooker manufacturers might consider the addition of a built-in water-heating unit.

Simmering has not received the attention it deserves, particularly for small quantities of food such as are required in infant feeding, where modern methods require simmering for 1–3 hours. The principle of using three elements in series to obtain the necessary small power causes an increase of plate diameter that results in inefficient use of the boiling-plate when small quantities of food are simmering. I suggest that simmering should be done with a separate high-resistance element so disposed in the boiling-plate that the effective outside diameter of the element does not exceed, say, 4 in. The fifth position of the boiling-plate switch could be arranged to connect this element alone for simmering.

Mr. G. R. Peterson: With regard to Mr. Humphreys's paper, it seems to me that if there is an ideal balance as between heat conveyed by radiation and by convection in ovens, then eventually all cookers will tend towards this ideal. If this is so, the necessity for introducing the additional complication of a scale of heat numbers becomes unnecessary, and the thermometer could be made to read as usual in degrees Fahrenheit, or, if preferred, the

number 1 could be used to signify 100° F., the number 2 to signify 200° F., and so on.

With regard to Mr. Waite's paper, in considering the economic aspect of supply for cooking purposes the author points out that the very large number of cookers which are connected to his system has not materially increased his system peak-load. I notice in the load curves for a summer weekday (Fig. 1) a pronounced peak attributable to cooking load at about noon, but the curves for a winter weekday (Fig. 2) give only slight evidence of any such peaks caused by cooking. This fact, taken in conjunction with the low consumption figure of about 900 units per annum for consumers with cookers installed, shown in Table 1, leads me to suggest that a large number of such consumers do not use their electric cookers in the winter but probably rely on a coal-fired range.

In Table 2 the author gives an economic justification of supply for cooking purposes. The figures quoted are, however, somewhat better than could be obtained by many undertakings, particularly those purchasing their supplies in bulk. For instance, the figure of 5 % for distribution losses seems on the low side, and the figure of 0·1748d. per unit, which presumably includes distribution losses, is also a good deal less than many undertakings have to pay with coal at the price it is to-day.

The economic balance drawn by the author is, however, incomplete, as no information is given as to the capital charges assumed in connection with the cookers themselves, or as to the receipts for cooker rentals. I feel that this additional information would add greatly to the value of the paper.

Mr. R. Mellor: In my opinion the automatically-controlled electric oven has come to stay, and decisions will have to be made as to whether standard ovens now on circuit are to be converted to automatic control; as naturally the question of obsolescence of existing apparatus plays the greatest part in the success of schemes for the development of the domestic load.

On page 576 Mr. Humphreys states that the sheathed-wire griller-boiler cannot be used for grilling and boiling simultaneously; I should like to bring to his notice the fact that well over 3 000 of the cookers supplied on hire by my previous undertaking were equipped with this particular type of griller-boiler, and the practical results and recommendations of actual consumers were that it gave satisfactory service for all purposes.

With regard to Table 2 of Mr. Humphreys's paper, it would be interesting to know the boiling-time of the new 1 800-watt sheathed-wire element using a thin-based utensil as compared with the figure of 9·4 minutes given for the cast-iron embedded plate using Vessel D (an expensive machined-bottom aluminium pan). I think the result of such a test would prove that equal speed of boiling could be obtained without the expense of special pans which is essential with solid-type plates.

I should like to know whether it would be possible for the manufacturers' standard cooker to be so designed as to accept either (*a*) a solid-type griller-boiler, or (*b*) a radiant-type griller-boiler; as I feel that such a design would meet with immediate success.

The information given in Mr. Waite's paper is borne out by the following statistics which have been obtained from the Carlisle electricity undertaking and also from a large undertaking with which I was at one time associated.

Referring to Table 7, no indication is given as to whether the figures are compiled for houses having cookers only (i.e. so far as hired apparatus is concerned) or whether the averages include consumptions for consumers hiring cookers, water heaters, and/or wash boilers. The figures in Table C are average consumptions obtained since 1934, when all domestic consumers on the undertakings in question were split up into categories of various rateable values. For ease of comparison, the rateable values have been adjusted so as to coincide with those put forward in the paper. Assuming that the author's figures are for houses having electric cookers, it will be seen that the figures given by him compare very favourably with those in Table C. With the tariffs available the actual cost incurred for cooking in houses of £15 rateable value is approximately 2d. per day; this sum includes the hire charge of the cooker and the cost of any additional energy consumed.

Table C

Rateable value	Without hired appliances	Including hired cookers	Including hired cookers, water heaters, wash boilers
	kWh per annum	kWh per annum	kWh per annum
£15	300	1 060	1 930
£16 to £30	486	1 610	3 390
£31 and over	1 820	3 430	5 370

On page 589 the author states " the only possible way of marketing cookers is by means of straightforward hire or rental." Many of the larger undertakings and power companies are now adopting the policy of changing over from hire to hire-purchase for a period of 7 or 8 years, including free maintenance, and I should like to know whether he considers that any retardation in the output of cookers would result if such a scheme were adopted by his own undertaking.

The reference to economic rentals is rather interesting, for my own experience is that such rentals have a retarding effect on the growth of connections. I should like to know whether the hire charges adopted by the author are economically sound or are based on the principle of part subsidization out of revenue.

I assume that his reference to proper cooking utensils relates to machined-bottomed pans. If this is so, I cannot entirely agree with the remarks regarding the provision of special utensils, as I feel that the use of radiant-type plates, not necessarily the transformer-operated type, overcomes this objection. I base this opinion on the following experience. In order to reduce the number of complaints arising from the use of improper-type utensils on solid boiling-plates, it was decided to hire a complete set of flat-bottom aluminium utensils at a charge of 1s. per quarter. Further, with every cooker put out on hire a machined-bottom utensil was supplied, and a special point was made of this when the demonstrator called, the

saving in time being demonstrated by boiling a certain quantity of water in the consumer's pan and comparing this with the time taken to boil the same quantity in the special pan supplied with the cooker. Despite all this, at the end of 3 years it was found that only 48 % of the consumers had taken advantage of the scheme. In addition to this unsatisfactory state of affairs, trouble was being experienced due to the fairly high cost of reconditioning pans, and so it was decided to change over to the sheath type of plate. The result has proved that this decision was more than justified.

I cannot entirely agree with the author that the manufacturer i' in the best position to know what is required as regards the design of electric cookers. Rather I would suggest that the engineer of an undertaking similar to the author's, who is maintaining over 15 000 cookers, is in the best position to recommend modifications to cooker designs which would tend to eliminate the numerous small complaints received from users. I think it would be to the manufacturers' ultimate advantage if their designers were to spend a short time in the reconditioning shops of large undertakings. They would then be able to see for themselves the defects which arise in practice, and incorporate in new designs the modifications necessary to eliminate these defects.

Perhaps the most interesting section of the paper is that which relates to the statistics of maintenance costs given in Table 11. Here again it may be of interest to the author to have the figures appertaining to the undertaking to which I am attached. Since March, 1937, separate costing has been allocated to the maintenance and the reconditioning work, the former term covering all the work done on the consumers' premises. Material used and all labour charges in connection with the cleaning and modifying of cookers in the workshops is charged to reconditioning. This, broadly speaking, is the same position as that prevailing at Hull, with the exception of cooker removals; these being chargeable, so far as Carlisle is concerned, to maintenance.

The costs for the 9 months ending 31st December, 1937, are as follows:—

Maintenance		
Total	£596	
Average cost per cooker (1 029) . .		11s. 7d.
Reconditioning		
Total	£220	
Average cost per cooker connected		4s. 3d.

To arrive at the average cost, the average number of cookers in use was taken, on the same basis as that specified by the author. The costs make provision for transport, material used, and labour involved; and when a cooker is reconditioned the finished article has to be indistinguishable from new, as no reduction is made in hire charges.

Referring once again to Table 11, I should be glad if the author could give me some indication as to what has been included under the items " replacement of non-electrical equipment " and " miscellaneous."

In conclusion, I should like to suggest that undertakings should adopt for the reconditioning and maintenance of cookers similar methods of costing to those given by Mr. Waite, as I feel certain that a summary of such costs would prove of value to all engineers faced with the problem of maintaining large numbers of domestic appliances on hire.

[The authors' replies to this discussion will be found on page 615.]

NORTH MIDLAND CENTRE, AT LEEDS, 15TH FEBRUARY, 1938

Mr. C. F. Wells: It is doubtful whether thermostats are yet sufficiently reliable to last the life of the cooker, and they may increase maintenance costs.

I would point out that visits to consumers' premises by well-trained demonstrators do much to popularize electric cookers.

It would be useful if the figures given by Mr. Humphreys with regard to tests of boiling-plates could be supplemented by inclusion of the efficiencies.

Mr. K. C. Coop: I am interested to note the change brought about in the temperature/time curve of an oven by alteration of the position of the thermostat; is not the distribution of temperature dependent also to some extent on the position of the food in the oven? Will Mr. Humphreys inform us whether the curves shown in his paper were obtained on an empty or a full oven, and what effect he considers that the mass of food has on the time cycle of the thermostat?

Dr. E. C. Walton: I have one or two general remarks to make with regard to Mr. Humphreys's paper.

First, it would be interesting to know what are the advantages of putting the heating elements at the bottom of an oven. The disadvantages are obvious: the temperature of the lining at the bottom of the oven is so high that spilled liquids and fats are a very great nuisance.

Can the author tell us anything about the effect of the colour of the radiating surfaces in the oven on the heating of the food, or about the effect of the colour of the utensil surfaces? Clearly, these colours will play some part, particularly in ovens in which most of the heat-transfer is by radiation.

I should like to know how the author measured his oven temperatures in the experiments on thermostatic control. Has he any comments to make regarding the relative importance of the effects produced by the two factors—radiation and convection—on the temperatures as given in the experimental curves? If a small thermocouple was used, quite probably radiation had little effect.

Mr. C. G. Nobbs: I agree with the author that the oven of the future will be thermostatically controlled. In the early days of thermostats I had some experience of the design of the B.K. oven, the elements of which were enclosed inside heating plates of large area to induce convection currents and reduce radiation to a minimum. An even heating effect and extreme sensitivity of control were obtained by binding the thermostat stem to the elements, or enclosing it in the element plate.

I had hoped to learn from these papers something of the thermal-storage cooker from the electricity supply point of view. Electric cooking demonstrators may be

against teaching a different kind of cooking, but first-class cookers of the solid-fuel thermal-storage type are coming into public favour.

The oven designer will never get to finality and low prices by adopting the ideas of individual housewives or cooks; he must try to pool all the ideas obtained from the thousands of cookers tried out, fix a standard, and produce in large quantities. Mr. Waite has gone a long way in adopting a standard cooker and low-price units, but a good thermostatically-controlled oven might prove to be that little additional step which would increase sales of cookers and units.

Slot meters of the kind that return a " dividend " to the consumer for unconsumed units have a good psychological effect.

Mr. G. A. Vowles: Until quite recently I attached little or no importance to the necessity for automatic control of oven temperatures, but recently my ideas have been revised as the result of conversations with various ladies who are intimately connected with the intricacies of cooking. They have mentioned an aspect of cooking that has not occurred to many men, namely the idea of cooking at lower temperatures that can be maintained with the low heat continuously on, or at a temperature ranging between that obtained with medium continuously on and top, which normally can only be obtained by continuous hand regulation.

In my opinion it does not matter whether the thermostat is graduated in Centigrade or Fahrenheit degrees or has an arbitrary scale marked A, B, C, D, or 1, 2, 3, since the cook using any particular cooker would soon establish her own data.

Turning to Mr. Waite's paper, I should like to comment on the question of the load curves that were shown us.

I agree that we are attaching far too much importance to the possibility of moving the time of peak loads. Surely the fact that we are incurring a peak load of x kilowatts more at 10.30 on a particular morning, as compared with the evenings of a few years ago, has no real bearing on the development or the cultivation of domestic loads. The fact that during last winter on a certain Monday at 10.30 a.m. the maximum load of the year was indicated is no proof that the domestic wash-boiler was responsible. Such a peak load was experienced on our own system at Halifax. It only exceeded the evening peak by 100–200 kW, and was brought about by a combination of circumstances: first, it happened to be a very foggy morning; secondly, it was also very frosty; and finally, these conditions chanced to occur on a Monday when we expect the majority of the washing to be done. But apart from this aspect I see no objection to creating peaks in both morning and evening. Certainly the peak in the morning will seldom exceed the peaks experienced in the past in the late afternoon, since just as lighting can be demanded in the morning so cooking in a good many homes provides a load for the system in both afternoon and evening. The general result is all to the benefit of the undertaking, as it helps to fill up the dips at present existing in our daily load curves, and certainly improves our station load-factor.

[The authors' replies to this discussion will be found on page 615.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 1ST MARCH, 1938

Mr. J. L. Carr: Attempts to develop the domestic load amongst the less affluent consumers are worthy of considerable support; but it is unwise to base conclusions for general development upon one particular example. The case referred to in Mr. Waite's paper relates to 500 houses where limited use is made of electricity for domestic purposes. The characteristics of that supply are interesting, and are similar to those obtained in some other places; they do not, however, represent finality in development.

The author states that the tariff is an important point in the development of the domestic load. People near the lower income level are, however, unable to meet the accumulating bills; and some means of gradual payment is necessary if considerable use of electricity is to be encouraged. The provision of electric cooking is only an initial step; and if other uses should be fostered, the need for some form of easy payment becomes even more pressing. In the case of the rehousing flats in Manchester, where electrical apparatus is provided as part of the equipment, consumers are using on the average considerably more than the figure cited. In one block of some 200 flats the first year's average approximated 1 600 kWh, at the low running charge of ½d., the supply being given through prepayment meters.

The author's method of assessing the supply cost is open to criticism. In Table 2 the generation fixed-charge is given as £3 1s. 5d. per kW, the transmission fixed charge is given as 8s. 8d. per kW, and " other fixed charges," which ostensibly include management, rates, etc., are expressed as a kW charge on the coincident demand. Again, on page 586 the whole of the cost is expressed per kW of coincident demand, divided by the diversity factor between domestic and other supplies. I would point out that distribution costs are to a large extent dependent upon the number of consumers, and vary only slightly with the distribution load; they are not governed by the coincident load. Generation and part of the transmission costs, on the other hand, are related to the coincident maximum load. Management charges are more closely related to the number of consumers than to the coincident load. It is important that this question of cost should be viewed in the correct perspective, otherwise misleading conclusions may be drawn.

A misuse of terms appears in Table 1, where a load factor is calculated from the actual consumption and that part of the load which coincides with the generating maximum. A value derived on this basis may easily exceed 100 %. Further, in Table 5 a very considerable increase in load factor is suggested: but the value here is derived from kWh sold and undertaking's maximum load, and is likely to be influenced considerably by local conditions of distribution. Published returns for Wimbledon give correct load-factor values considerably higher, but less variable, than the figures in Table 5.

The domestic load possesses considerable diversity

within itself and also with other loads. The load characteristic for a lower wage group shows marked deviation from the load for the average consumer; and variations with locality are also to be found. In Manchester, for example, the cooking load displays four distinct peaks—in the morning, at midday, in the early evening, and also at about 10 p.m. The maximum cooking load occurs at midday on Saturday and is equalled by that at midday on Sunday. With less affluent consumers, reduced use is made of the cooker during the week; the morning maximum generally occurs earlier and is more spread out than in the average case; and the other peaks are much less pronounced: the maximum load definitely occurs at the week-end. In other areas, where the major meal is taken in the evening, three peaks are indicated, the last of which overlaps the system maximum to a greater extent: the maximum load occurs on a weekday.

It is interesting to note that in the district with which the author is associated over 80 % of the dwellings may be regarded as in the poorer class.

wire heating element for grillers, and says it is very satisfactory. It may be satisfactory for some forms of grilling, but it is not for those forms which require a very high degree of radiant heat.

I endorse the statement by Mr. Humphreys on page 572 that " It may be argued . . . that the manual control of electric ovens is so simple that the thermostat cannot possibly have much to offer, but experience shows this view to be mistaken." In February, 1936, in a discussion on " Gas versus Electricity," he said that " although thermostats were fitted to gas cookers some years ago, there is not yet any indication of demands for such assistance from users of electrical cookers." I should like to point out that Mr. Humphreys does not contradict himself, as he includes the phrase " from users of electric cookers ": the demand for the automatic oven does not come from users but from prospective users. When we adopted the automatic control of ovens it lifted our output of cookers by 55 % during a period when the expected increase was 22 %; this indicates that automatic control is a distinct attraction. I would urge

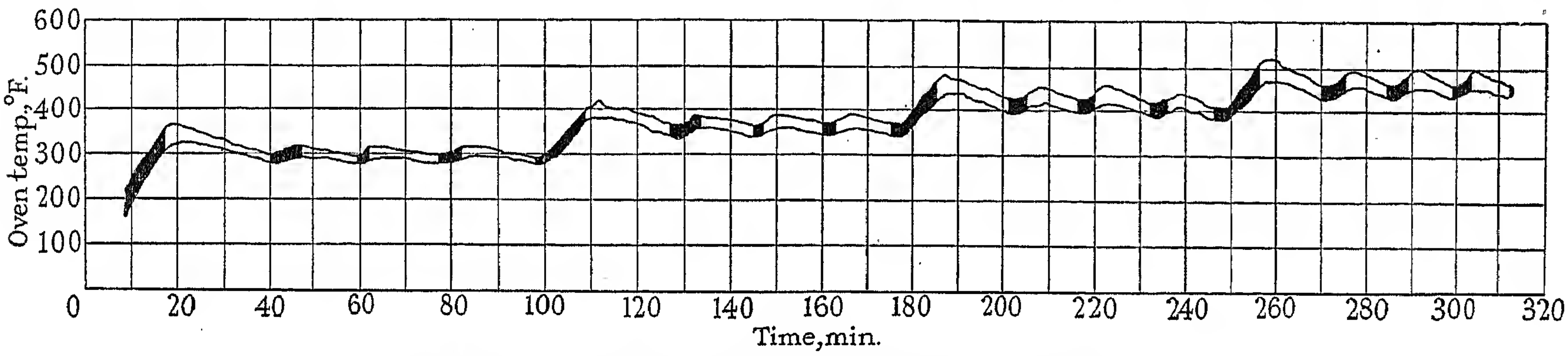

Fig. F.—Test with thermostat as in Fig. 6: empty oven.

NOTE.—Shaded portions show the periods during which the thermostat is " on."

Mr. O. Howarth: Mr. Humphreys refers to the griller-boiler; the ordinary griller-boiler may be a griller but is far from being a boiler. It will not boil fast enough. Some say that we should not try to boil on the griller top; but in a house having no gas service there is no other means of boiling, except the coal fire. A kettle is not sufficient, as it is only used for boiling water. The supreme test of the griller-boiler is: Can fried potatoes be made on it? Because it is essential, if one is to make satisfactory fried potatoes, that when the potatoes are put in, the fat must quickly come back to the boiling point. With the usual griller-boiler it does not do so.

We constructed a griller consisting of two plates 7 in. × 4½ in. arranged side by side, giving a total of 9 in. × 7 in., the plates being of fairly thin stainless steel and having vertical ribs on the under-side. Between these ribs, elements were mounted having the minimum of refractory material. The loading was 1 200 watts per plate, a total of 2 400 watts. We found this to be an excellent griller, and almost as fast as the radiant-type boiling-plate used as a boiler. Such a griller mounted in a roomy, open frame with two 2-way and " off " switches arranged to switch either plate on, both plates on full, or the two plates in series, makes a much more useful appliance than the conventional pattern of griller-boiler, and should be cheaper to construct. There is undoubtedly a considerable market for such an appliance.

On page 576 Mr. Humphreys refers to the sheathed-

manufacturers of automatic ovens to remember that the old type of wireless control has been abandoned in favour of a control which can be easily seen. The position of a pointer can be seen much more clearly than a disc with numbers round its circumference. We commenced using cookers with automatic oven control in January, 1936, and we soon found that there was no demand for 3-heat cookers, so we dropped them. There is no doubt that much discredit has been cast upon automatic control by the use of unsatisfactory designs.

A considerable amount of work on automatic oven control has been done in the testing laboratories of the Lancashire Electric Power Co. prior to, and since, the automatic cooker was standardized at the beginning of 1936. In plotting our results we have shown the maximum and minimum temperatures in the cooking space in the oven. We have found that the most satisfactory oven is one with the elements behind side shields at each side and with a certain amount of heat supplied from underneath the floor of the oven. The side shields act as flues, and encourage circulation of the air, and the elements underneath the floor of the oven ensure an even temperature in the lower part of the oven when the presence of food tends to interfere with the circulation.

Fig. F shows the results of tests with the thermostat in a position corresponding to Mr. Humphreys's Fig. 6, and Fig. G shows the results obtained with the same cooker with the thermostat in the position corresponding

to his Fig. 7. Fig. H shows the temperature conditions in the same oven, and arranged for Fig. G, when baking a light fruit cake.

Tests on a number of samples indicate that insufficient attention is given by many designers to the correct application of automatic oven control, the thermostats themselves being wrongly placed, and the oven designs being such that automatic control cannot be satisfactorily adopted. This has undoubtedly discredited the automatic control of electric ovens. We are satisfied from the results of tests on many different types, and from actual experience in service, that the most satisfactory oven is one in which radiant heat is kept down to the absolute minimum. Our standard practice has been to have degrees Fahrenheit marked on the thermostat dial plate. We have had no difficulty due to this, and I am unable to understand the mentality of those who prefer a number, which is almost meaningless until converted into degrees, when the numbers may just as easily indicate degrees Fahrenheit (providing the oven is a well-designed one).

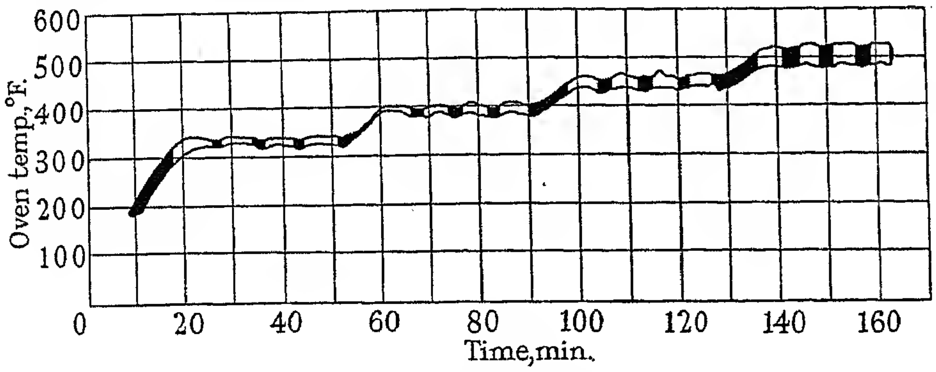

Fig. G.—Tests with thermostat as in Fig. 7: empty oven.

NOTE.—Shaded portions show the periods during which the thermostat is "on."

There is undoubtedly an enormous market for a cheap oven which can be used in conjunction with the grill to which I have previously referred. We have made up and tested an oven consisting of a tin box inside a galvanized-iron case and separated from it by an air space, the oven being fitted with a thermostat. Fig. J shows that this arrangement warms up very quickly. Tests made show that its losses are not more than 10 % higher than those of a conventional design of oven having the same dimensions. These losses are more than offset by the saving in electricity during the warming-up period. Such an oven, which should be cheap to construct, would meet a large, and as yet untouched, market.

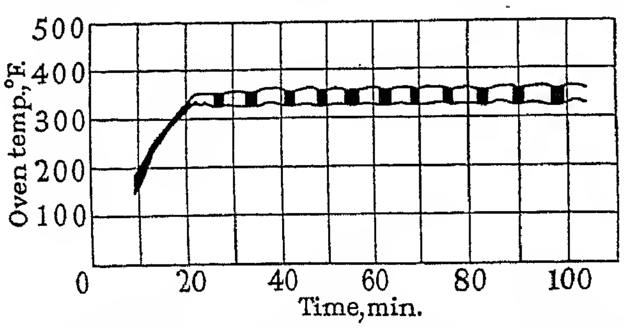

Fig. H.—Tests with thermostat as in Fig. 7: baking light fruit cake.

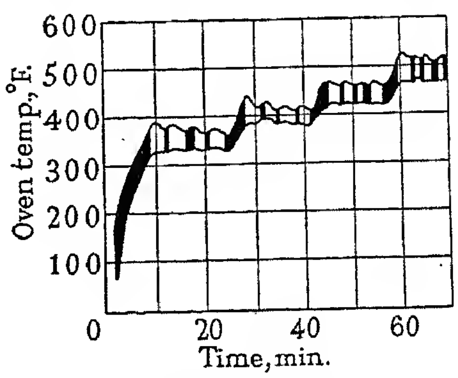

Fig. J.—Tests with tin-box oven.

NOTE.—Shaded portions show the periods during which the thermostat is "on."

On page 588 Mr. Waite refers to the use of slot meters, and I should like to ask whether a higher price per unit is charged for slot-meter supplies in order to cover the average cost. Has he made use of two-part-tariff slot meters? These are eminently suitable for the class of work he describes, particularly those with provision for a variable fixed charge.

I agree that the electric cooker is a new kind of household tool which requires in its use a somewhat different technique from its predecessors, but I suggest it should be a technique which is much easier for the user to get accustomed to than is the case with some designs of electric cookers.

On page 591 Mr. Waite says, " Automatic regulation of oven temperature is a new development which has many desirable features, and is certain to be popular with housewives. Increase in hiring charge will tend to discount this popularity." The experience of the Lancashire Electric Power Co. is that discouragement in the shape of an additional shilling per quarter is not sufficient to prevent new customers wanting automatic oven control. We also find that those who have mastered the technique of 3-heat cookers are not particularly anxious to have thermostats fitted to their cookers; this indicates that there is not much risk of a big demand to convert the cookers which are now out in service.

I should like to know whether Mr. Waite's figure for the annual maintenance cost per cooker—14s. 1d.—includes the cost of the building and all overhead charges in connection with it. Our figure for the same items, but excluding buildings, is 11s. 5d.: this is for hire-purchase cookers, and we should expect a higher figure for hired cookers. What are the hire charges for the various cookers, and does he include a kettle with every cooker? If so, is it of the modern type with immersion element, or of the old type with bolted-on elements? It is our custom to put the main switch and kettle plug on the cooker, and in many instances we find

that the absence of a control panel or switch on the wall is a distinct attraction to the customer.

Mr. J. Sharples: Referring to Mr. Humphreys's paper, I am reminded by the description of the "General construction features" (page 566) of a point which has often occurred to me. Whereas warming-cupboard doors are always arranged on the drop-down principle, oven doors are nearly always of the side-hinged type, although I should have thought that the extra shelf accommodation provided by a drop-down door would be very useful when the positions of materials inside the oven were being changed. Do mechanical or economical reasons dictate the preference for side-hinged oven doors, or is it due to the conservatism of the consumers and/or supply authorities?

On page 576 the author states that the sheathed-wire type of griller-boiler cannot be used for grilling and boiling simultaneously unless the kettle or saucepan is spaced away from the heating element, thereby greatly reducing the speed of boiling. It should be pointed out that at least one firm supplies a cheap copper kettle with corrugated base for use with this type of griller-boiler, and this type of utensil enables a boiling time of approximately 12 minutes to be obtained for 3 pints of water with a loading of 1 750 watts, which can be considered a good performance for a dual-purpose plate. At the same time, the corrugated base of the utensil allows the sheathed-wire elements to retain a sufficiently high temperature for all normal grilling purposes.

We are told on page 577 that the upper limit of loading for the cast-iron embedded plate is determined by casting temperature, but on page 578 a statement follows to the effect that as higher wire temperatures become possible, the upper limit of loading may be set by the insulating properties of the embedding cement. These statements appear contradictory and require explanation. Does the author mean that the insulation will be the determining factor when higher wire temperatures, and higher casting temperatures, become possible? What is the present permissible maximum casting temperature?

The figures given on page 579 with regard to the length of the coils on an 8-inch cast-iron embedded plate are rather meaningless unless other particulars such as wire diameter, number of turns per inch, and coil diameter, are stated. It would have been better to supply figures relating to current densities, and I should like the author to state the current densities obtained on modern cast-iron embedded plates of 2 250 watts and 1 800 watts loading respectively, and also on a sheathed-wire radiant plate of 1 800 watts loading.

To what extent is the wire temperature of 800° C., given as the figure obtained on a 2 250-watt cast-iron plate under steady conditions with no vessel, affected if a vessel with a concave polished bottom is used? It would appear that under the latter conditions the wire temperature may reach an unsafe figure in view of the fact that Fig. 10 shows that the *casting* temperature of an 1 800-watt plate may be as high as 720° C. under similar conditions.

I find myself rather puzzled by the figures for insulation resistance given in Table 1, namely 60 000 ohms for a 2 250-watt plate and 250 000 ohms for an 1 800-watt plate of the same dimensions. I remember that the preliminary announcements in the Press of the advent of the higher-loaded plate stated that the increase in loading had been obtained without increase of wire temperature. If this is so, why is the insulation resistance so much lower? Does it mean that the same wire temperature has been achieved by increasing the diameter of the coil, with a consequent increase in wire length accompanied by a decrease in insulation thickness, or is the lower insulation resistance due to an increased casting temperature?

Dealing with Mr. Waite's paper, I notice that on page 589 he mentions that a selection of special cooking utensils for use with electric boiling-plates should be displayed in the supply authority's showrooms, and that consumers should be invited to hire or hire-purchase these on reasonable terms. This is, of course, a very desirable object, particularly when the cooker is fitted with cast-iron embedded plates, which largely depend for their efficiency on good contact between plate and utensil, but what percentage of the consumers take advantage of such a scheme? I know of one large supply authority which inaugurated a scheme whereby consumers could hire three different utensils on very reasonable terms, but after this scheme had been in operation for 4 years less than 50 % of the electric-cooker users had taken advantage of it. In view of this, I should be interested to know what Mr. Waite's experience has been in the matter.

The author considers that consumers who insist on speedy boiling are best dealt with by getting them to hire or purchase an electric kettle as an adjunct to the cooker. Since in these cases the kettles would be carrying out duties normally performed by the boiling-plates on the cooker, I think the paper should have included details of their maintenance costs.

I should like to express my agreement with Mr. Waite's remarks on this matter of speedy boiling. I think that some supply authorities tend to exaggerate the desire for fast boiling on the part of their consumers, and are therefore apt to push cooker manufacturers to the limit to provide high-loaded boiling-plates. Provided a reasonable boiling time can be obtained, say 3 pints of water boiled in 10 or 11 minutes, the plate with the highest efficiency, other points being equal, should be adopted in preference to high-loaded plates which achieve speedy boiling at the expense of relatively high consumption, which leads to higher bills and possible dissatisfaction with the electric cooker. Manufacturers should be allowed to utilize recent advances in the qualities of resistance alloys and insulating materials to increase reliability, and not be forced to offset these advances by increasing the boiling-plate loadings. The challenge of the gas cooker can be met on the score of convenience, cleanliness, healthiness, and even economy, and, once these qualities are appreciated by the housewife, the latter will, as Mr. Waite says, quickly adapt herself to any small alterations in cooking times which may be necessary.

I note that Mr. Waite is of the opinion that it is unsafe to introduce the "quick-boiling boiling-plate" on undertakings which still have both a.c. and d.c. networks, owing to the fact that the "normal design" of the quick-boiling plate cannot be used on d.c. He is

obviously of the opinion that quick boiling can only be obtained with the low-voltage transformer-operated plate, but this view is certainly not borne out by independent tests. It is only necessary to turn to Table 2 of Mr. Humphreys's paper to see that the lowest boiling time obtained with the low-voltage plate is higher than the lowest boiling times obtained with the sheathed-wire or cast-iron embedded plates, even though its loading is considerably higher. The low-voltage plate is only a quick boiler if considered psychologically; actually its efficiency is low and its use will lead to the high consumption to which I have referred above.

Mr. G. F. Sills: The oven is the most difficult and the most uncertain factor in cooking, and an accurate thermostatically-controlled oven relieves the cook in a number of ways. The following are the advantages of an automatic oven: (1) It is cleaner, as the food can be cooked at a lower temperature. (2) It involves less maintenance, as the temperature-rise—even if one forgets to switch off—will not be higher than the oven is capable of withstanding. (3) In the event of a heat indicator being provided, this will not go beyond its safe limit. (4) It can be given a higher wattage loading, which in itself decreases the pre-heating time without the consumption of any more units. (5) High-temperature cooking of the pastry type can be carried out with the same ease as plainer cooking. (6) Long-period cooking operations are easy, as the thermostat will maintain low temperatures accurately throughout the period desired. (7) It gives the housewife additional freedom, inasmuch as once the thermostat has been set for the desired temperature, which the user knows from instructions will be reached in a certain time, that temperature will be maintained as long as required. (8) When automatic oven control becomes a standard feature, it will be more convenient for the user on moving from one district to another, and possibly having to use a different make of cooker. (9) With the automatically controlled oven, voltage variation is automatically compensated for, diversity factor is improved, and it has even been suggested by one large undertaking that the maximum demand is reduced; this is an advantage from the point of view of bulk supply.

The reason why the drop-down oven door is not in more common use is that it has the following disadvantages: (*a*) It creates more of a vacuum and lets more heat out of the oven than the ordinary door. (*b*) It has to be opened right down to enable one to see what is in the bottom of the oven. (*c*) It is more expensive to make. (*d*) It is more costly to maintain.

The choice of a thermostat is most important, and from inquiries which I have made I believe that the rod type is much superior; as it is decidedly more robust, more accurate in the first place, and will keep its accuracy within very close limits over the life of the cooker.

Mr. R. C. Hawkins: As a consumer I should like to emphasize one or two points which have a bearing on the question I am personally interested in, and that is the general development not only of domestic supplies but of all supplies. As far as cookers are concerned, Mr. Humphreys really sums up the whole situation in his notes under the general heading "Factors affecting development and design." He particularly deprecates the frequent changes in external appearance of cookers which have been put on the market from time to time. We must all agree with him on that.

I should like to ask what difference is there really between "high standard of performance" and "efficiency."

Mr. Waite refers to the collecting of standing charges with the rent. I presume that in Hull, as in some other places, he has been able to make arrangements with the owners of property for their collectors to collect the standing charge. I should like to know what success he has had in that direction, as experience seems to vary from town to town, and will he state exactly what is the Brighton tariff?

On page 589 he stresses, and I think it cannot be stressed too much, that the cooker rental charge should include the wiring and the control switch. I was also glad to read that he equips his service men with electric vehicles.

On page 593 he refers to Junior cookers, and I take it he means the breakfast cooker. If that is the case I am very interested to hear that he has so many of that type, because whilst it does not obviously bring in the same revenue as the full-size cooker, it has played an important part in introducing the electric idea into thousands of small homes.

He suggested that the life of a cooker might be taken as 20 years for the purpose of calculating depreciation. Whilst I am not personally in a position to comment on that, it is very much higher than my supply-engineer friends usually indicate.

Mr. N. Ashton (*communicated*): I agree with Mr. Humphreys regarding the question of a simplified indication on the indicator for thermostatically-controlled ovens, and would suggest that manufacturers might endeavour to produce a simple scale of a uniform type. This would be a tremendous help to consumers who transfer from one supply authority to another.

With regard to the matter of oven lagging, it would be helpful if Mr. Humphreys would give more details regarding the application of aluminium foil, since the application of slag wool, which is at present very widely used, necessitates great care with regard to the vitreous enamelling; care is also necessary in view of the fact that the handling of slag wool should be minimized.

The practice, mentioned by Mr. Waite on page 591, of removing cookers at each change of tenancy, and completely de-greasing and overhauling, has two notable disadvantages. In the first place, many cookers do not require this expensive attention, and the fitting of a new oven interior and other minor details as required on site is sufficient in many cases to put the cooker in new condition again, with less change and reconditioning costs. Secondly, I think Mr. Waite loses a splendid opportunity of advertising his cookers, by removing them entirely instead of having a cooker on site which will be seen as prospective tenants come to view the house.

I should be glad if Mr. Waite could give some further information in connection with Tables 9, 10, and 11 in his paper. It is noted from Table 9 that a further 3 500 cookers were connected to the mains in 1937; and whilst Table 10 shows 720 less service calls on boiling plates, Table 11 shows an increase in boiling-plate maintenance costs of £112.

THE AUTHORS' REPLIES TO THE LONDON, BIRMINGHAM, NEWCASTLE, LEEDS, AND MANCHESTER DISCUSSIONS

Mr. O. W. Humphreys (*in reply*): A number of speakers have raised points of a general nature which emphasize my remarks concerning the effect of the method of distribution on cooker design. Hire and hire-purchase systems involve very real problems of obsolescence, and the tendency of the supply authorities to deprecate frequent changes is easily understandable. Provided, however, that this problem is viewed in proper perspective, it should be possible to assure Mr. Clough that there is no reason why hire should depress quality. The method of development will be affected, changes being confined chiefly to those having a real technical value and being introduced at long intervals. Progress is likely to take the form of occasional radical changes instead of frequent minor ones. If fears concerning obsolescence are allowed to take precedence of all other considerations, then, of course, progress will be stifled.

That a hire system demands that ease of maintenance should weigh heavily in design has been rightly emphasized by Mr. Margary and Mr. Whyman. Mr. Warrilow laments the lack of imagination in cooker design, and the failure of anything of a revolutionary nature to find acceptance. Undoubtedly the absence of direct contact between the manufacturer and the potential cooker user is partly responsible, but it may be questioned whether the user would have gained, on balance, had the very sound, if somewhat conservative, lines which development has followed been replaced by more spectacular, but less firmly based, progress.

The burning-out of the ends of oven heating-element coils to which Mr. Warrilow refers is most probably due to their being clamped between brass washers. Under the influence of heat the zinc is evaporated from the brass and attacks the nickel-chromium. The trouble can be overcome by the use of nickel, or nickel-plated steel, washers.

Mr. Swingler makes a good point in connection with the "comfort" appeal of electric cookers in warm climates. In view of his remarks concerning the preference of kitchen-proud South African housewives for cookers of American and Canadian design, it is interesting to note the increasing demand for the standard home-model British cookers which is now being experienced in that market and also other overseas markets.

Mr. Ellerd-Styles expresses a preference, which will be shared by many, for table-type cookers. Such models are available, but their inherently higher cost, and the difficulty of accommodating them in many modern kitchens, prevent their becoming serious competitors of the pedestal type.

Mrs. Williams, Mr. Onley, and others, have offered very sound suggestions with respect to points of a very practical nature in design which manufacturers would do well to bear in mind whenever new designs are in course of preparation. The long-standing controversy concerning the relative merits of the drop-down and side-hinged door, raised again by Mr. Sharples, is likely to continue so long as man is capable of independent thought, but, from the points of view of mechanical simplicity and cost, the advantage is certainly with the side hinge.

The difficulty of meeting Prof. Cramp's request for silent switches arises from a desire to maintain interchangeability of cookers as between a.c. and d.c. supplies, but with the ever-increasing preponderance of alternating current the silent switch is sure to find wide application.

I should like to thank Mr. Whibley for stressing the desirability of co-operation between manufacturers and supply authorities, to ensure that the latter are well equipped with the technical information necessary to enable them to reply immediately to consumers' queries. Consumer education plays a vital part in the popularizing of the various applications of electricity, and the supply authority, with its closer contacts with the consumer, is in general in a far better position than the manufacturer to carry out this important work. In the same way Miss Hooper rightly emphasizes the importance of including with cookers really detailed instructions.

I share Mr. Ward's view that vitreous enamel may eventually be superseded as an external finish, but at the moment it is difficult to see any indication of the form that its successor is likely to take.

I think Mr. Hawkins will appreciate the distinction between the terms "high standard of performance" and "efficiency" used in the paper, if I say I have throughout used the latter expression in its strictly scientific sense, i.e. to indicate the ratio of the energy usefully used to the total energy dissipated. Thus, for example, by increasing the loading of a boiling-plate to 10 kW the standard of performance would be greatly improved, but efficiency would almost certainly be decreased.

I agree with Prof. Cramp that aluminium foil is a very attractive lagging from many points of view. Mr. Ashton asks for information as to methods of application. Probably the two following methods, both of which are covered by patents, are the best known in this country. In the first, very thin foil is crumpled in such a way that the crumpled sheet has an effective thickness of about 1 cm., and the number of sheets necessary to give the required lagging thickness are wrapped around the object to be lagged. In the second a transversely corrugated strip of foil is secured by means of wire clips to a flat strip. The depth of the corrugations is usually $\frac{1}{2}$ in. or $\frac{3}{4}$ in. This material is applied in a similar way to the crumpled foil, and in both cases the foil is protected by means of a suitable outer casing.

The clamping of heating elements to the outside of the oven interior, as suggested by Mr. Gilling, has many points in its favour but involves a number of serious technical difficulties, of which that of finding an easy method of replacing burnt-out elements is one. The arrangement has been used and, I believe, abandoned, by at least one manufacturer.

In reply to Dr. Walton I would say that it is usually found easier to obtain uniform oven-heating if some bottom heat is provided. The emissivity of radiating surfaces in the oven influences the distribution of the heat transfer as between radiation and convection, but as long as vitreous enamel is used emissivity is independent of colour.

Thermostatic oven control.

It has been very interesting to find how generally thermostatic control is now accepted and appreciated. Many speakers who, like myself, were sceptical when the system was first introduced have now been converted, and I think that the very cogent arguments which they have put forward in its favour constitute the best answer to the few who remain to be convinced. Mr. Ward feels that thermostatic control is not necessary. Experience over many years proves him right; but although not a necessity it is a most valuable luxury. It enables an unskilled cook to get better results, and a good cook to get good results more easily. Mr. Wells expresses doubt concerning the ability of thermostats to give good service throughout the life of the cooker. This is a point which demands most careful attention, but personally I am satisfied that the very high standard required can be and, in general, is being attained.

The curves given in the paper were obtained with the ovens empty, and Mr. Coop rightly points out that the shape of the curves will be influenced by the introduction of food into the ovens. Practical cooking-tests have shown, however, that, with experience, performance can safely be judged from tests on an empty oven; such tests are, of course, considerably easier to carry out under strictly controlled conditions. In reply to Dr. Walton, the temperatures were measured by means of fine-wire thermocouples. They are therefore very nearly true oven air temperatures, as the readings of the couples will be scarcely affected by radiation.

The only serious difference of opinion in connection with thermostatic control appears to be that concerning the marking of the thermostat scale. Most speakers followed Mr. Townley's lead in support of the view that some sort of standardization is desirable, so that the present chaotic conditions, which necessitate the preparation of a special instruction book for each type of cooker, may be ended. Mr. Vowles, it is true, feels that the matter is unimportant because a cook will get used to anything, but surely it is politic, as well as considerate, not to extend unduly one's calls on her adaptability. Discussion has hinged chiefly round the question as to whether the standard scale, when it is eventually produced, shall be marked in degrees Fahrenheit or "heat numbers." Mr. Bernard strongly supports the retention of the Fahrenheit scale on the grounds that its meaning is generally understood, and that the use of heat numbers necessitates calibration by means of actual cooking-tests. Mr. Howarth bases his preference for the temperature scale on the contention that heat numbers are quite meaningless. I quite agree that the readings of a thermometer calibrated to read true oven temperature have a very precise meaning, but as they completely ignore the contribution of radiation to the heating condition of the oven, the quantity which they indicate with accuracy is one in which the cook is not interested. Admittedly she will with a little experience find out for herself the relation between the thermometer reading and the heating condition, but should she change her cooker the period of testing and experimenting will have to be repeated. Similarly she cannot use, without experiment, recipes published in the Press or elsewhere, because there is no common language in which precise instructions can be given.

If the thermometer is not calibrated to read true oven temperature, but, as some people advocate, is arbitrarily calibrated so that readings indicate some agreed oven conditions described as "very hot," "hot" and so on, the readings become of real value. As, however, they definitely do not denote the temperature of anything in degrees Fahrenheit, the justification for the retention of the name is hard to find. Furthermore, it must be noted that, before standardization can be reached, definitions of the various oven conditions have to be found; and these can only be based on the rate of heat transfer. Pending development of more precise methods, calibration by cooking-tests would be essential. If a scale of heat numbers were adopted it would certainly not be meaningless, for each number would indicate a definite rate of heat transfer—so many calories per cm^2 per sec.—to an object in the oven, under certain clearly specified conditions. The scale would therefore have as precise a meaning as the Fahrenheit temperature scale, and would indicate a property of the oven which is of vital importance to the user, whereas the latter scale does not.

I agree with Prof. Cramp that this question is of sufficient importance to warrant the attention of the British Standards Institution, but before they could usefully take action a good deal of spade work would have to be done by some such body as the Electrical Research Association.

Mr. Peterson visualizes the Utopia in which, the ideal balance between convective and radiant heat-transfer having been found, air temperature will serve completely to define heating condition. This happy state will, I fear, prove as unattainable as the others which have borne that name.

Boiling-plates.

The earthing of boiling-plates, the importance of which is very rightly stressed by Mr. Townley, is raised by Mr. Heppenstall from the point of view of the effect of leakage current on the operation of an earth-leakage trip. If the plate is earthed only through a leakage trip there are conditions under which the leakage current may be high enough to cause the trip to operate, but if the plate is earthed directly, as well as through the leakage trip, such conditions are very unlikely to arise. The lives of boiling-plates vary so enormously with the conditions of use that I am afraid it is impossible to give Mr. Heppenstall the information he asks for in this connection. Laboratory figures are available, but as these apply to test conditions differing from those of normal use they are valueless without careful interpretation.

Both Mr. McLean and Mr. Wilson express a desire for more boiling-plates on a cooker. Special cookers with abnormally generous boiling-plate equipment are available, but experience seems to show that, so far as most users are concerned, the number of plates normally provided represents the most acceptable compromise between facilities and cost.

Mr. McLean will find full details of the test conditions applicable to the figures in Table 2 in British Standard Specification No. 744—1937. All tests were from cold. While I have no figures available for the very latest exposed-resistor boiling-plates, such figures as I have for earlier models do not confirm Mr. McLean's contention

that tests on smaller quantities of water would have shown this type of plate in a more favourable light.

Mr. Mellor has appreciated the good performance which can be obtained with a sheathed-wire plate used in conjunction with a thin-bottomed kettle. I think he is possibly not aware, however, that such utensils also give excellent results with cast-iron plates. Boiling is sometimes actually faster than with machined-bottomed utensils.

The efficiencies corresponding to the boiling times in Table 2, asked for by Mr. Wells, are given in Table D.

In reply to Mr. Rawll's question concerning the figures given in the paper for insulation resistance, I would point out that the figure of 60 000 ohms applies to a 2 250-watt plate, and that of 250 000 ohms to one loaded to 1 800 watts.

Prof. Cramp will be interested to know that aluminium cooking-vessels with blackened bases used to be commercially available. I am not sure if they can still be obtained.

ture of the refractory is already considerably higher than in the cast-iron type, and stability of insulation under severe conditions of use has even now to receive serious consideration.

It is difficult to give figures for current densities in heating-coils, since these naturally vary quite widely for the products of different manufacturers. It was for this reason that, in the paper, I referred to coil length. The ability of the cast-iron plate to accommodate a much longer coil than the sheathed-wire type naturally enables the designer to work to a much lower current density.

If a 2 250-watt cast-iron plate were used under such conditions that the casting reached a temperature of 720° C., the wire temperature would still be under 950° C. The life of the wire at this temperature would be quite good, but, as the casting would almost certainly crack in a very short time, the behaviour of the wire would be of little more than academic interest.

With reference to Mr. Sharples's final point, it is true that the *maximum* temperature of the casting in the first

Table D

Effect of Curvature and Finish of Base of Vessels on Efficiency for Various Types of Boiling-Plates

(Efficiencies corresponding to boiling times given in Table 2.)

Boiling-plate		Efficiency, with 3 pints of water: vessel as stated					
Type	Loading	Thin aluminium			Heavy (machined bottom) aluminium		Vitreous-enamelled iron
	watts	Vessel A	Vessel B	Vessel C	Vessel D	Vessel E	Vessel F
Cast-iron embedded	1 800	55 %	48 %	41 %	61 %	61 %	40 %
Sheathed-wire	1 500	53 %	56 %	54 %	58 %	59 %	62 %
Low-voltage exposed resistor . .	2 250	29 %	31 %	30 %	32 %	38 %	40 %

Mr. Gilling expresses preference for the sheathed-wire plate on account of its high efficiency. Mr. Ward, while granting to this type of plate the advantages of psychological appeal and freedom of choice of vessel, considers the cast-iron plate to be the best all-round proposition. Mr. Townley admits that he is a convert from the sheathed-wire to the cast-iron plate. All I would do in reply to these speakers is to emphasize the importance of taking all properties into account when comparing plates—every type has at least one feature in which it is superior to all others—and to repeat the general statement that a high standard of performance may be of greater importance than high thermal efficiency.

It would appear from Mr. Sharples's remarks that I have not made myself quite clear concerning the influence of the various component parts of a boiling-plate on permissible loading. With the cast-iron plate, at the moment, the limit is very definitely set by the casting. If, through improvement of the casting, higher loadings became possible, the new limit might be determined by consideration of either the rate of oxidization of the resistor or the stability of the insulation. At present there is a good deal in hand in both these directions. In the sheathed-wire plate, on the other hand, the tempera-

2 250-watt cast-iron plate to be put on the market was substantially the same as in the earlier 1 800-watt plate. The *average* temperature was higher, however, as the more heavily loaded plate was so designed that the temperature gradient across its surface was lower. The 2 250-watt plate therefore has a longer coil, embedded in refractory at a higher average temperature, and it is for this reason that its insulation resistance is lower.

I am in complete agreement with the speakers who have advocated the provision of facilities for hiring flat-bottomed vessels with cookers fitted with cast-iron plates. While it cannot be held that the use of such utensils is essential, the savings thereby effected in energy consumption more than justify their cost to the user, and the supply authority gains from the practical elimination of all risk of casting failure.

Griller-boilers.

I must agree with Mr. Howarth that the griller-boiler leaves much to be desired where speed and efficiency when used solely for boiling are concerned. Personally I feel that if the history of its development is considered it will be found that " griller-boiler " is really a misnomer, and that " griller-simmerer " would be a much more appro-

priate name, for the object of introducing the combined unit was to increase the simmering, rather than the quick-boiling, facilities of cookers. This is little consolation to the working-class housewife who has to be content with a very small cooker whose only boiling equipment is a griller-boiler, and if her difficulty cannot be solved by the provision of a cooker with more complete facilities which she can afford, the problem of the development of a fast-boiling griller-boiler becomes one of considerable urgency.

The boiling efficiencies of griller-boilers vary so widely for different types that it is difficult to give Mr. Whibley the information for which he asks. If high efficiency is important, however, the sheet-metal-topped or sheathed-wire unit is certainly superior to that provided with a cast-iron top.

Mr. Mellor asks if it would be possible to design a standard cooker to take either a sheathed-wire or open-coil type of griller-boiler. The only technical difficulty would be that the open-coil element, being situated beneath some form of metal top-plate, would be at a lower level than the sheathed-wire element. This would have to be taken into account when laying out the positions of the grill-pan runners, and it would be necessary to make sure that the hob and front structure of the cooker did not prevent the grill pan from being placed sufficiently near to the heating element of the sheathed-wire griller-boiler.

Heat storage cookers.

For a full discussion of the advantages of the storage type of cooker from the point of view of electricity supply, I would refer Mr. Nobbs to the articles mentioned on page 566 of the paper. These advantages can be very briefly summarized as follows, the importance of various points varying with local conditions:—

The maximum demand on the supply system cannot, under any circumstances, exceed a predetermined value which, unless diversity is very high, is substantially lower than that of normal-type cookers.

The load factor is unity and the annual consumption is guaranteed. Both costs and revenue can therefore be very accurately determined.

Distribution is simplified and cheapened, not only on account of the low current required, but also because voltage-drop due to each cooker is constant and, especially where long lines are used, ability to allow for this drop when adjusting the substation voltage permits a substantial increase in current for a given size of conductor.

Finally, the absence of heating-elements operating at high temperatures, and the simplification of the wiring and switching, effect a considerable reduction in maintenance costs.

Mr. J. N. Waite (*in reply*):

General.

Some contributors to the discussions question the accuracy of my method of dealing with fixed charges in Table 2, and suggest that certain items of fixed cost, particularly management and rates, are not properly allocable on the basis of demand.

In determining cost allocation it is known that it is impossible to obtain the cost of supplying each individual consumer; nor can the average cost of the whole supply be accepted as being representative of the actual cost to each consumer, or as an equitable charge for every consumer. Predominant, however, is the fact that every demand which is included in the undertaking's peak demand (for which all resources are necessary) does cost the equivalent of its share of the cost of maximum demand. As the cost of each individual consumer cannot be determined, it becomes necessary to place those consumers having the same characteristics of demand into separate classes, in an attempt to determine the cost of supplying each class.

Accepting this, and also accepting the fact that all the demands at the time of the peak demand must bear their fair proportion of the expenses necessary to supply that peak, then it naturally follows that an endeavour must be made to distribute this cost to the consumers in each class in relation to the diversity which exists between the particular class and the other classes contributing to the peak.

While even off-peak consumers do affect the fixed costs to a small degree, the effect of such consumers is so different in degree from that of a normal consumer that the difference in degree amounts practically to a difference in kind and, in tariff-making, is dealt with as such and need not be dealt with here.

In dealing with tariffs and costs of the normal consumer the broad principles which must be accepted are:—

(1) The maximum load of the undertaking is the real factor which controls the fixed costs of the undertaking, and therefore maximum load is the only logical basis for allocation of fixed costs.

(2) The cost so determined is the average cost of all classes of supply afforded, and includes the effect of (A) diversity of demand *between* different classes; (B) diversity of demand *within* each class.

(3) Equitable allocation of cost to the particular class of supply (class being determined by similarity of characteristics of supply conditions) is the average peak cost applied to the diversity established for the class.

Applying the foregoing principles, the difficulties and differentiations set up by the contributors to the discussion do not arise, and due allowance is made automatically for the passing on to each class of the benefits created by the class diversity.

The foregoing is not affected in any way by the time when the undertaking maximum-demand occurs; what does matter is the peak demand—the time is immaterial. The question of "on-peak" and "off-peak" demands is covered automatically by the application of the diversity existing within and between the classes.

In connection with management cost, so far as generation and main transmission are concerned, it is at once obvious that the critics' suggestion that management cost should be allocated on the basis of number of consumers is quite inadmissible; for the costs of generation and transmission are common to all classes of consumers, and the magnitude is determined by the magnitude of the maximum load of the undertaking and has no direct connection with the number of consumers. There are many other expenses included in management costs, such as expenses of the Electricity Commissioners, change-of-

frequency levy, general staff salaries, publicity, etc., which cannot be correlated to number of consumers or, indeed, to any particular class.

It is possible that the critics had in mind the fact that more consumers mean more meter readers, clerks, etc.; but these are not management costs and are normally allocated under other headings.

Consideration of the foregoing leads irresistibly to the conclusion that the only practicable method of allocation of all fixed costs is on the basis of the general average fixed cost in relation to peak demand.

In connection with rates, the same reasoning applies, although the facts and incidence differ. The sum to be paid for rates depends primarily upon profit. Profit is the difference between costs and income; 80 % of the cost is represented by fixed cost, which, in effect, is controlled by maximum demand. Therefore it appears not only logical but also equitable to allocate rates cost on the basis of maximum demand, and each consumer will then bear approximately the proper portion of rates cost.

The raising of the question of the allocation of rates on an equitable basis brings an interesting sidelight into view affecting domestic consumers. The rating assessment of an undertaking is arrived at on the well-known "hypothetical tenant" basis. In arriving at the rental which a hypothetical tenant would pay, certain allowances are made, amongst which is an amount for interest on tenant's capital. An undertaking which has carried out considerable domestic development work will have increased its tenant's capital by the capital value of the domestic apparatus out on hire or hire-purchase, and therefore the allowance for use of tenant's capital will be increased. The effect of such allowance is to decrease appreciably the rating assessment. Hence, for a given margin of profit, the undertaking with extensive domestic development and large tenant's capital will have a lower rating assessment than a corresponding undertaking with little or no domestic development. From this it might legitimately be argued that the costs of domestic consumers should be credited with this reduction in rating assessment, for it has been effected by the supply to the domestic class of consumer alone, and the purist would contend that the people who create the advantage should receive the advantage.

The critics of Table 2 appear to have overlooked the fact that the second item of expenditure in the Table already includes the proper allocation of management and rate charges, and all fixed charges not included in the first three items are covered by the fourth item, this representing the balance of fixed charges not already included. If the critics' suggestions were carried out, domestic consumers would be debited with a number of fixed costs twice over. It may be pointed out that the first item in Table 2 is the capital charge on the local distribution. This is the actual amount incurred in this particular case. As it was in the nature of an experiment, a separate cost allocation of all capital expenditure for local distribution was made, including land for substation site, substation, and equipment, mains, services, meters, etc. It is submitted that Table 2 does represent the true facts as nearly as they can be ascertained, and the method employed is more correct than would be the case if the suggestions of the critics were employed.

A number of contributors to the discussion have asked for the hire charges, and particulars of the cookers used. Questions have also been asked about the electric kettles.

Four sizes of cookers are hired out. The finish for all sizes is light mottled-grey vitreous enamel.

		Loading watts
Junior Cooker:		
Oven interior:	12 in. × $10\frac{1}{2}$ in. × 12 in.	1 900
Hot cupboard:	18 in. × $5\frac{1}{2}$ in. × 12 in.	
Grill-boiler:		
bottom:	11 in. × 8 in.	
top:	9 in. × 7 in.	1 800
Boiling-plate:	One 8 in.	1 800
Small Cooker:		
Oven interior:	13 in. × 13 in. × 12 in.	2 200
Hot cupboard:	19 in. × $5\frac{1}{2}$ in. × 12 in.	
Grill-boiler:		
bottom:	11 in. × 8 in.	
top:	9 in. × 7 in.	1 800
Boiling-plate:	One 8 in.	1 800
Medium Cooker:		
Oven interior:	14 in. × 14 in. × 13 in.	2 600
Hot cupboard:	$19\frac{1}{2}$ in. × $5\frac{1}{2}$ in. × 14 in.	
Grill-boiler:		
bottom:	11 in. × 8 in.	
top:	9 in. × 7 in.	1 800
Boiling-plates:	One 8 in.	1 800
	One $6\frac{1}{4}$ in.	1 000
Large Cooker:		
Oven interior:	15 in. × 15 in. × 15 in.	3 000
Hot cupboard:	$21\frac{1}{2}$ in. × $6\frac{1}{2}$ in. × $16\frac{1}{2}$ in.	
Grill-boiler:		
bottom:	12 in. × 9 in.	
top:	$10\frac{1}{2}$ in. × 7 in.	2 000
Boiling-plates:	One 8 in.	1 800
	One $6\frac{1}{4}$ in.	1 000

All sizes of cookers are fitted with a warming cupboard and grill-boiler. The two sizes given above for the latter are the size of the grill and the boiling-plate respectively. It will be seen that the grill-boilers and boiling-plates are standardized as far as possible for all sizes.

The hiring charges per quarter are:

	With wiring	Without wiring
Junior cooker:	4s.	3s.
Small cooker:	5s. 6d.	4s.
Medium cooker:	7s.	5s. 6d.
Large cooker:	8s.	6s. 6d.

The kettle-hire scheme is entirely separate from the cooker-hire scheme. The kettles are of 3-pint capacity, with elements clamped to the underside of the base. All kettles are fitted with a temperature-controlled automatic plug ejector which will cut off the current if boiled dry. The normal hiring charge is 1s. 6d. per quarter. Originally the kettles had a copper finish. When the superior chromium-finished kettle was introduced, the hire charge of the copper finish was reduced to 1s. per quarter. A number of the copper-finished kettles accumulated in stock despite the reduction in rental, and these

were reconditioned and sold outright at a reduced price and were deleted from capital account and records.

With reasonably good maintenance the life of a kettle would appear to be much longer than is usually credited. Quite a large number of kettles have been in service for 9 years and still appear good for many more years of service. The average life will certainly be more than 10 years.

The economic results of the kettle-hiring scheme are as follows at 31st March, 1938:

Total cost of kettles: £16 439	
Capital charges at $3\frac{1}{2}$ %, and	£
10 years of life	1 976
Maintenance	1 831
Total expenditure	3 807
Income from rentals ..	4 255
Surplus ..	£ 448

The maintenance cost comes out at approximately 2s. 6d. per kettle per annum. It will be seen that the rentals are economic even on a 10 years' life.

Several speakers question the suggestion in the paper that it would be justifiable to take 20 years as the economic life of a modern electric cooker with vitreous-enamel finish and a high standard of maintenance. It appears probable that the speakers are unduly influenced by the experiences with earlier types of cookers with ordinary enamel finish and exposed-type heating-elements. My suggestion is based on the fact that cookers have been in use on my undertaking for 9 years approximately, and that they still look well and function properly. It is thus obvious that the figure of 7 to 10 years' life usually taken must be an underestimate of the economic life with the conditions postulated. In view of this it is not equitable to debit higher capital charges than are actually incurred to existing consumers. At the moment there is not sufficient data to settle authoritatively this debatable point, but my experience suggests that it would be legitimate to take at least 15 years as the life, and probably (apart from possible changes of fashion) 20 years would be nearer to the true actual value.

A number of speakers insist that the rapid boiling of small quantities of water is a matter of considerable importance, in opposition to the opinion expressed in the paper. A matter of this sort must always remain a matter of opinion. With a house equipped with a small-displacement water heater, boiling water can be obtained in 2–3 minutes with the aid of an electric kettle. If a particular consumer attaches importance to this point it is quite easy to cater for the particular requirement without blaming the standard electric cooker, which, in effect, is a multi-purpose tool. An engineer surely should recognize that special wants justify special tools, and he should not expect a multi-service tool to carry out a special purpose as effectively as a tool devoted to the special purpose. So long as the reasonable requirements of the average user are met at the lowest possible cost, it appears to me to indicate a lack of the sense of proportion to attach so much importance to a very minor point, and I adhere strongly to the opinions given in the paper.

Much the same line of argument applies to the radiant low-voltage exposed-resistor boiling-plate. The special transformer required puts up the first cost and consequently the hiring charge, and I have been unable to discover what real advantage is gained by the increase in cost. The results given by Mr. Humphreys indicated that it does not produce any quicker boiling—in fact, the reverse.

London.

It is pleasing to note that the results quoted by Mr. Townley confirm the data in the paper to the effect that large-scale domestic electrification produces a high combined load factor, and also that he agrees that a high standard of service for prompt attention to complaints is essential.

With reference to hiring-out of cooking utensils, urged by Mrs. Pocklington, it must be pointed out that removals are relatively frequent and experience indicates that practically no consumer would accept utensils that had been previously used. The return of the utensils would put up the cost appreciably. Hence it was decided that an attempt should be made to develop the domestic cooking-load without hiring special utensils. The attempt proved successful.

Mr. Harmer agrees with me in stating that the so-called "all in" or "equated" tariff penalizes good consumers. When based on the rateable value, the value of the percentage used for the fixed part of the domestic tariff has to be correlated to the general level of assessment in use in the particular area. The assessment level in Hull is relatively very low, and it is probable that 15 % produces somewhere about the same cash value as $6\frac{1}{2}$ % does in Hammersmith for the same type of property. The step-rate prepayment meter is one way of dealing with a particular difficulty, and I should not hesitate to use it if it were the only way. It has to be borne in mind that the step-rate meter is more complicated and costly than the normal integrating watt-hour meter. Both my method and the step-rate meter of Mr. Harmer fulfil their function of promoting domestic electrification in low-income houses, and therefore the only real point at issue is which method produces the lowest overall cost. I am satisfied that my own method produces as low a cost as any other. I cannot accept the statement that an electric cooker does not require a different technique in its use from that used with a coal fire or a gas cooker. The electric cooker undoubtedly does require a different method of use, and it is here suggested that technique and common sense are really interchangeable terms. The demonstrators do not talk of either, but show how to do normal cooking operations with the electric cooker to the best advantage. I also equipped all the domestic-science schools with electric cookers free of cost when the cooking campaign was first started, and the teachers cooked similar meals on electric and gas cookers. By measuring the cost of each form of energy, the opinion previously held that electric cooking was the dearer method was effectually dispelled. Pilot lamps are not fitted, but provision is made so that the consumer can have one if desired.

Mr. Ellerd-Styles is in error in ascribing a municipally-owned gas undertaking to Hull. The gas supply is company-owned. The laying of gas supplies was not

prohibited on the estate referred to. Gas mains were not laid, presumably because with the electrical equipment of the houses it would have been uneconomic. As explained in the paper, this particular housing estate is tenanted by very low-income tenants, hence the results do not represent the average income for working-class dwellings but the lowest value to be expected with domestic electrification. It was undertaken as an experiment, and the results are considered to be satisfactory. The average number of units per house per annum for 1937 and 1938 are 895 and 960 respectively, so that the decrease in units for the 1938 year is only 9·4 % and not 20 %. Consumptions fluctuate from year to year, and it is advisable to base judgment on the average of several years. While the units have decreased so has the maximum demand, and it should not be forgotten that approximately half the income comes from the fixed charge, so that the decrease in revenue is not proportional to units. In any case, as shown the decrease is small, and as the average was used my conclusions were justified.

24·17 % of the total sold. The slight increase in price of large-power units over the last 2 years is due to the increase in cost of coal. With these results it is difficult to conceive that the domestic units do not bear their proper proportion of the total costs. Table E gives the national figures from the Electricity Commissioners' Statistical Returns.

These are not quite so good as the figures in Table 4, for lighting and domestic units are not separated, but the same trend is indicated unmistakably. All classes of units have been reduced in price, while the only class which has appreciably increased in magnitude as a percentage of total sales is the lighting and domestic class. This appears to me reasonable proof that not only is domestic supply economic on the tariffs now obtaining, but that by increasing the diversity the domestic demand has lowered the general costs and other consumers have shared the benefit created. Whilst it is not contended that the whole of the cost reduction has been effected by the increase in domestic units, it is reasonable to assume that domestic units have been a contributory cause, and therefore the relatively low price for these is justified.

Table E

Year	Lighting, heating, and domestic		Public lighting		Traction		Power		Total
	Price per unit	% of total sales	Price per unit	% of total sales	Price per unit	% of total sales	Price per unit	% of total sales	Price per unit
	d.		d.		d.		d.		d.
1929	3·05	26·1	1·69	1·6	0·88	9·1	0·86	63·2	1·44
1930	2·86	27·0	1·61	1·7	0·81	8·9	0·82	62·4	1·38
1931	2·67	30·2	1·54	1·8	0·77	8·8	0·81	59·2	1·38
1932	2·54	32·4	1·49	1·9	0·73	8·5	0·79	57·2	1·36
1933	2·41	34·0	1·39	1·9	0·67	8·3	0·77	55·8	1·33
1934	2·28	34·2	1·30	1·9	0·63	8·2	0·73	55·7	1·26
1935	2·13	34·8	1·26	1·9	0·61	7·4	0·69	55·9	1·20
1936	1·92	36·6	1·17	1·8	0·59	6·8	0·66	54·8	1·12
1937	1·79	37·6	1·10	1·8	0·58	6·3	0·65	54·3	1·08

Mr. McLean takes a comparison for an equation. The figures were selected so that the comparison was simple. The fact that the comparison gave identical values was purely fortuitous.

Mr. Rowson extends the theory of trusteeship far beyond what was set out in the paper, which merely suggests that those in control of the public supply of electricity are in the position of trustees for the public supply of electricity alone. It does not appear to be reasonable to place upon them the duty of safeguarding the nation's capital resources and avoiding nationally wasteful competition. His examination of the economics of domestic electrification, while interesting, is far from conclusive, for he arrives at the conclusion that the general case for domestic electrification is not proven. I submit that the contrary is the case, and the actual results of undertakings over the last decade supply all the proof that is necessary. Table 4 in the paper gives the results of the Hull undertaking over a period of 16 years. Domestic electrification commenced in the year ended 31st March, 1930, and the results for 9 years since that time show decreases in the average price received from all classes of consumers. During that period the units sold under the domestic tariff increased from 4·91 % to

Mr. Rowson's comment that distribution charges in Hull have fallen very considerably since 1932 bears out the foregoing contentions.

I would refer Mr. Rowson to my " General " reply for an answer to his criticism of certain economic results. I would specially direct his attention to the paragraph dealing with rating assessment and the effect of tenant's capital on the same, and I would also stress to him that management charges and rates for generation are already included in the fixed charge for generation. Surely he does not consider it equitable to make the same charge twice over to the same consumer.

His criticism of the 5 % loss allowable in Table 2 on the kW demand appears to indicate a lack of appreciation of what is actually being allowed for, which is the instantaneous loss at the time of the undertaking peak between the power-station busbars and the substation low-tension bars. This loss is composed of the voltage-drop in the high-tension feeders (in this case of the order of less than 2 %) and the transformer loss. The low-tension network losses do not enter into this at all. His suggestion that a 10 % loss should be allowed for is negatived by the

above, and, incidentally, very little consideration of the problem from the aspect of voltage regulation would show that his suggested value is utterly impracticable.

His suggestion that the Hull figure of 16 % loss between units generated and units sold should be used in Table 2 again appears to indicate lack of appreciation, for the unit cost is calculated on units sold not on units generated, and his suggestion would result in the consumer being debited with the total losses twice over. Incidentally, it may be mentioned that Hull still contains a large d.c. network (now in the process of being superseded by a.c.) and therefore the average loss is greater than exists on the a.c. networks. The estate being considered has a.c. distribution. His arguments about domestic load factor and diversity show the same lack of appreciation of what is being claimed in the paper, for he states that if the load factor were calculated on sales it would be reduced from 41·3 % to 33·8 %. The load factor given in the paper is already calculated on units sold, and it is obviously entirely wrong to reduce it as suggested. The same faulty reasoning is found in his criticism of the analysis of the Wimbledon figures. This analysis estimates the actual demand of all the different classes at the time of the peak and uses units sold to arrive at the load factor of the domestic units.

Mr. Rowson's attention is directed to Mr. Swingler's contribution, where he records an increase in output from 65 to 192 million units in 7 years, due to increase of domestic units, during which the load factor of the undertaking has remained constant at 43–46 %. It would appear that Mr. Rowson's contentions with regard to the load factor of domestic supply are at variance with ascertained fact.

His statement that service and meter apparently attract no interest or repair charges is incorrect. They are included, and he again would charge these twice over. His table showing a loss of 718d. for every 3 504 domestic units sold is based on a series of misconceptions. If this figure were correct, the loss at Hull on the domestic units would be of the order of £40 000 for last year.

If the average prices for the different classes in Table 4 are studied, together with the fact that the net profit of the Hull undertaking, after meeting all charges, was of the order of £60 000 for the last financial year, it needs very little consideration to indicate that his conclusions are unreliable. If Mr. Rowson objects to his table being applied to Hull results, it has to be pointed out that he is attempting to make a case against domestic supply generally. The grid tariff applies to only a small proportion of the total units of the country. The majority of the units sold are sold by " selected station " undertakings, and their costs are appreciably lower than the grid tariff. So that both his facts and his reasoning are unsound. His argument about the hypothetical consumer who would level up the load curve at Hull is a good example of fallacious reasoning. A so-called " off-peak " consumer only gets the low price because his demand is " off-peak." Any demand coming on the peak must be charged for and naturally would be, so that if the conditions of the consumer changed, so would his price. In my opinion the argument advanced has no relation to the subject dealt with.

If Mr. Rowson's conclusions are correct, then all the development over the last two decades has been unsound economically. The actual results show beyond reasonable doubt that his conclusions are unsound, for they do not accord with established facts.

Mr. Swingler's contribution to the discussion is valuable from many points of view. It illustrates very clearly how a change of actual conditions, atmospheric temperature, standard of living, etc., influence the methods to be adopted by electricity-supply authorities who are dealing with the same problems. Change in conditions often necessitates change of methods.

So far as water-heating is concerned, in this country quite large development can, and has, been achieved with a follow-on rate of ½d. per unit, and the business to be obtained at ⅓d. per unit is relatively enormous. So long as the undertaking peak is in the afternoon, it is safe to assume that domestic water-heating will make very little demand at peak hours, for the normal habits of the people will ensure this. With the peak occurring towards midday, the demand made by domestic water-heating may be expected to be higher than in the late afternoon, and probably anti-peak precautions may be necessary.

The relatively high atmospheric temperature in Durban will be a very valuable selling agency for electric cookers and will enable progress to be made, even with costs much higher than those ruling in this country. Mr. Swingler's experience of the development of sales from 65 millions to 192 millions over a period of 7 years, mainly due to increase in sales of domestic units, with the load factor remaining steady at from 43–46 % confirms the facts and arguments put forward in the paper about the load factor from large-scale domestic electrification being of a relatively high order. It also discounts the views of Mr. Rowson.

The record of success of the cooker hire-purchase scheme in Cape Town deserves the highest commendation, but experience in this country would appear to indicate that such progress could not be made here with hire-purchase, owing to the difference in conditions.

His remarks about consumers being allowed freedom of choice from a reasonable number of good makes are probably justified with a hire-purchase scheme, but I do not agree that they are applicable to a straight hire scheme, which is the general practice in this country. Progress here is largely dominated by total cost. In addition, a multiplicity of hiring charges is not a desirable feature, and, further, freedom of choice would make maintenance somewhat more costly and difficult owing to the multiplicity of spares that would be needed. Different localities need different methods. Mr. Swingler has proved his methods successful under his conditions, while many British undertakings have proved the methods advocated in the paper to be successful under their conditions. Conditions dominate methods.

The two load curves are extremely interesting, and show very clearly the tremendous influence of domestic electrification. Whether the supply authorities believe it or not, there is a great public demand for the services of electricity in the home, and this demand will have to be met or, alternatively, it will have to be proved beyond doubt that it cannot be met on an economic basis. I believe that the services can be given on an economic basis.

Birmingham.

With reference to Mr. Rawll's question, the item of £2 12s. 11d. described as "Other fixed charges" in Table 2 covers all other fixed charges such as management, rates, etc., not already covered in the other items in the Table. The figures for load factor are based upon the load at the time of the undertaking's maximum load.

It is interesting to hear that the number of dissatisfied cooker consumers in Birmingham is less than 0·5 % per annum, based on the total cooker consumers. This is much smaller than the figure of 4·6 % given in the paper, but that figure is based on the total since the inception of the scheme and is not a yearly figure as given by Mr. Rawll, which probably explains a large part of the difference in values.

I agree with Miss Hooper that when the average housewife knows how to take care of, and properly use, her electric cooker the maintenance cost will be reduced. This will take some considerable time to achieve, and in the meantime the cost of cases of misuse and neglect will continue to swell the cost of maintenance.

Mr. Margary's point that quick boiling is of vital importance is dealt with in my "General" reply.

The suggestion by Mr. Onley that a pilot light fitted to the main switch will reduce maintenance costs has not, in our experience, been borne out, for we have tried that and, so far as we could ascertain, the pilot lamp has made no difference; hence we went over to a prominent indicator, which is cheaper in first cost and also less costly for the consumer to operate. This experience is what we would expect, for the naturally careful person needs no reminder, while the careless person will overlook any reminder or reminders, no matter how prominently they may be displayed. My undertaking has not suffered much from the second point.

The point of Mr. Dean that heavy, machined-based cooking utensils should be available for use in connection with electric cookers is dealt with in my reply to the London discussion. The question of the division of the fixed-charge portion of the rateable-value tariff into equal or unequal quarterly increments is largely a matter of opinion. My undertaking has tried both methods and came to the conclusion that the unequal method of one-third to each of the winter quarters and one-sixth to each of the summer quarters produced the least complaints.

Newcastle.

With reference to the question by Mr. Ward, the normal calibration of slot meters is from 1¼d. to 2d. in steps of ¼d. The changes in calibration which are found necessary are relatively very few, for experience proves a very reliable guide to the first setting, and after a year's service it is very seldom that any further change is necessary. The tendency is to leave the calibration on the high side so that there is always a credit balance, and consumers using slot meters welcome a cash rebate. The method has proved very popular with the consumers. The confirmation that quick-boiling boiling-plates are not necessary is welcome.

Mr. Heppenstall's information on the results from recorder charts taken in Newcastle in 1934 are extremely interesting, and give a lower value for peak demand than that shown in Table 1, which makes the economic case still more favourable.

His analysis of the overall economic result of domestic supply on this estate is interesting, but some of his assumptions with regard to costs are incorrect. The conditions on the estate are rather unusual. The whole of the 500 houses are owned by the Sutton Trustees, who keep a resident manager on the estate so that every detail of maintenance of the property receives careful and immediate attention. The cookers are hired by the Electricity Department to the owners and form part of the landlord's equipment of the houses. The rental of the cooker is included in the rental of the house. The landlord also provided the electric wash boilers, and all the wiring. Practically all defects of electrical apparatus are attended to by the resident manager. In the case of the cookers, the Electricity Department provides the necessary spares, so that the cost of maintenance in this case is relatively very low. As a matter of interest the maintenance cost of cookers on this estate has been kept separately, and comes out at the extraordinarily low figure of 2s. 2d. per cooker per annum. When the conditions are taken into account it will be realized that the only real cost in connection with these cookers is the value of the replacements in the form of boiling-plates and elements. As the cooker is the landlord's property, changes of tenancy do not necessitate changes of cooker.

The balance sheet is as follows:—

Capital outlay on cookers: £3 550 (just over £7 per cooker instead of £12 as assumed)

Capital charges at 4 % and 20 years' life ..	£262
Annual capital charge per cooker	10s. 6d.
Average maintenance cost	2s. 2d.
Total cost per annum	12s. 8d.
Hire charge to landlord per annum	12s.
Net deficit per cooker per annum	8d.

So that the overall economic result of electricity revenue and cooker rental is satisfactory.

This particular case does not represent average practice and was not, therefore, included in the paper.

Mr. Peterson suggests that the relatively low consumption of about 900 units per annum, and the obscuring of the morning peak in the winter time, point to the conclusion that many consumers do not use their cookers much in the winter time but rely on a coal-fired range. This is undoubtedly true of the particular houses in Table 1. These houses do not, however, represent the average of all cooker users. In houses with a higher income limit, the units per cooker per annum are of a higher order than 900. I would suggest that the masking of the morning peak is also contributed to by the demand of wash boilers, water heaters, and occasional space-heating. Mr. Peterson makes the same error as Mr. Rowson, in the London discussion, in stating that the 5 % allowance for converting the local demand to demand at the power station is too low. Whilst, of course, this is a distribution loss, it is not the distribution loss in the usual sense of that term; it is merely the pressure-drop from the power-station busbars to the substation low-pressure bars at a particular time, and if it is considered in this light it will be seen that the value is reasonable.

The figures used are for the Hull undertaking, which has relatively low costs. For a smaller undertaking on the grid tariff it would be necessary to increase the tariff slightly in order to compensate for the somewhat higher costs of bulk supply. The additional information asked for is given in my reply to Mr. Heppenstall.

The contribution of Mr. Mellor is particularly welcome for the additional data it gives. Table 7 of the paper gives the results for all houses which are on the domestic tariff, irrespective of equipment. There are, of course, many houses included which have no hired equipment, so that, to get comparable figures, Mr. Mellor will need to average all his three classes into one class. I am of the opinion that the substitution of hire-purchase for straight hire would retard development on my own undertaking. The cooker rentals charged were intended to be economic ones, but the cost of maintenance proved to be higher than allowed for in the estimate. After this proved to be the case, a careful examination was made and it was decided to continue the existing rentals, as the slight deficit would be covered by the available margin in the unit charge for supply. The question of special utensils is dealt with elsewhere.

Mr. Mellor's disagreement with the statement that the cooker manufacturer knows best how to make a satisfactory cooker really arises from my being too brief. I assumed that every undertaking would place the experience acquired in regard to maintenance at the disposal of the manufacturer, and so obviate faults in construction and design. With this included, Mr. Mellor would probably be in agreement with the statement in the paper. His statistics for maintenance and reconditioning agree very well with those given in the paper.

Leeds.

It is pleasing to note that Mr. Nobbs appreciates the good psychological effect of slot meters which return a " dividend " to consumers.

Mr. Vowles's contribution to the discussion regarding the unnecessary fears of what may happen if domestic electrification does produce a morning peak is very welcome, as bearing out one of my main contentions.

Manchester.

Mr. Carr's criticism of the method of assessing the supply cost is dealt with in my " General " reply. I do not agree that any misuse of terms occurs in Table 1. The full details of how the load factor is calculated are given, and therefore in this case there would be nothing inherently wrong in a value of over 100 %. The figures used in the paper for the Wimbledon undertaking were taken from the official report of the Wimbledon engineer and therefore should be reliable and correct. The information given that, in Manchester, four distinct peaks at different times of the day arising from cooking are observed, is interesting and bears out the contention of the paper that the great diversity of domestic electrification on a large scale is bound to, and does, produce a relatively high load factor for the undertaking.

In reply to Mr. Howarth, the same price is charged for slot-meter supplies as for a quarterly account. In Hull, no separate rentals are charged for any meter or measuring apparatus required by the undertaking. His comments on automatic regulation really apply to higher-income houses. The majority of cooker consumers in Hull are in the low-income class and any increase in hiring charge would be a deterrent to progress. The cost of the buildings used is not included in the maintenance cost given. The hire charges and the maintenance cost of kettles are given in the general reply. Kettles are not included with the cooker, but are dealt with under a separate hiring scheme. As the paper shows, 15 538 cookers and 15 022 kettles were on hire at the end of 1937, so that practically every cooker user has been persuaded to have a kettle also.

In reply to Mr. Sharples, the attention of all prospective and actual cooker users is drawn to the desirability of using heavy machined-based cooking utensils for use on the boiling-plates; but relatively few trouble to obtain them. The number obtained direct from the Hull undertaking during the same period as covered in Table 3 is 2 197, but that is no criterion as to the number actually in use, for a large number of shops now stock this type of utensil and, doubtless, many users obtain them from sources other than the Electricity Department. In all public and private demonstrations the advantages of this type of utensil are stressed. It is pleasing to get Mr. Sharples's confirmation that quick boiling of small quantities of hot water can be adequately dealt with by other means. The reference in the paper to quick-boiling boiling-plates should have been related to the low-voltage exposed-resistor type. The fact that these are not so efficient or effective as the solid type adds weight to the statement in the paper that it is not desirable to introduce them where a network comprises both a.c. and d.c. supplies.

For Mr. Hawkins's information, the Brighton tariff is one which originated in that town. Under this tariff a demand indicator is installed as well as an integrating watt-hour meter. The first hour's use of the demand is charged at a relatively high price per unit and subsequent use is at a lower rate. In Hull, the first hour's use is at 6d. per unit, the second 2 hours' use at $1\frac{1}{2}$d., the next 2 hours' use at $\frac{3}{4}$d., and all over at $\frac{1}{2}$d. per unit. It will be seen that it is a combination of a two-part tariff and graded block system of charging. The system of collection of the fixed portion of the tariff and hire charges in the rent has not yet been widely used, but it is hoped to get a large extension as time goes on. So far, the experience has been very favourable. The Junior cookers are not "breakfast" cookers, but small ordinary cookers sufficient for 2–3 persons. Full details are given in my " General " reply.

With reference to Mr. Ashton's comments, our experience leads to the conclusion that new tenants will not use a cooker that other people have been using. It would need too much detail investigation to give the information asked for on boiling-plate maintenance.

THE WEAR OF ELECTRICAL CONTACT POINTS*

By W. BETTERIDGE, B.Sc., Ph.D., and J. A. LAIRD.

(*Paper received 6th September*, 1937.)

SUMMARY

An examination has been made of the phenomena occurring during the operation of electrical contacts, with particular reference to the destructive effects produced on the contact points. Four main stages in the break of a current have been observed, of which the resistance rise, the arc, and the spark, are well known; intermediate between the resistance rise and the arc is a stage in which the gap between the contact points is bridged by a drop of molten metal; this latter is of great practical importance since it is of almost universal occurrence, causes well-marked transference of contact material, and, as the potential difference between the contact points is then only about 2 volts, it cannot be suppressed by modifications of the interrupted circuit. The voltage-current-length characteristics of the molten bridge between electrodes of platinum-iridium (25 per cent Ir) have been determined and are found to be of a similar form to those for an ordinary arc, i.e. voltage inversely proportional to current and directly proportional to length. The reason for such characteristics is not known.

The conditions of voltage and current necessary for the formation of the different stages are described, and the effects produced by typical simple circuits are dealt with.

Suggestions are made which should help to reduce the wear of contact points to a minimum.

INTRODUCTION

It is well known that when two contacts carrying current are separated the subsequent arc or spark will cause disintegration of the surfaces of the electrodes, and that this may take a number of different forms. Although this problem of contact wear has been the subject of various investigations from time to time, amongst which are those of Holm† and Williams,‡ it still appeared at times difficult to account for the behaviour of contacts under actual working conditions, as it frequently happened that contacts which had been run in exactly similar electrical circuits sometimes had a perfectly clean matt surface, while at other times transference of metal occurred from anode to cathode and even occasionally in the reverse direction. It was also noticed that tungsten contacts which had been arranged to operate without any visible sparking gave trouble in a very short time owing to the formation of oxide on a minute excrescence on one electrode, while a corresponding hollow was formed in the other one.

It was at first thought that these apparent anomalies might be caused by impurities in the electrode material, variation in the structure of the metal, the presence of oil or moisture, or even by dust particles between the contact faces, but as no definite proof of this could be obtained it was decided to examine the subject from the electrical side again, and to see whether consistent results could be obtained by employing simple circuits and slowly moving contact breakers. It was felt that if the various phenomena which occurred at make or break of contacts could be studied individually, and some reasonably simple explanation given for the physical effects caused by each phase, it would be of considerable help to the designer of electrical apparatus which relied solely upon the unfailing operation of contacts for satisfactory functioning.

Preliminary observations on the cathode-ray oscillograph revealed the fact that it is possible for four well-defined phases to occur on the break of a current; first a resistance stage, then one the nature of which was unknown, while third and fourth come the arc and spark stages respectively, and it is these and the effects associated with each that have been reviewed in the following paper, particular attention having been paid to the pre-arc stage, for, so far as the writers are aware, except for a reference to the transference of metal in the liquid state by Holm,† very little is known about this phase, and although arcing can be very destructive to contacts the total abolition of it causes serious trouble owing to the transference already mentioned.

THE STAGES IN THE BREAK OF A CIRCUIT

When electrical contacts are held together with a sufficient pressure and a current is passed between them no destructive action on the contact points takes place; it is only as a consequence of making and breaking the circuit that destruction occurs. This destruction can take several forms, chief of which are oxidation, vaporization, formation of a black deposit, and transference of material from one contact to another, resulting in the formation of pits and piles on the surfaces of the electrodes.

When two contacts between which a current is passing are separated, the fall of that current from its initial value to zero can be divided into several stages, each characterized by the potential difference between the contacts and by the mechanism of the conduction of the current. In practice it is unusual for all of these stages to occur at a single break because of the limitation imposed by the value of the initial current, the applied potential and the capacitance, resistance, and inductance of the whole circuit. The principal stages are as follows:—

(1) Increase of contact resistance due to decrease in pressure causing a small rise in potential, usually less than 0·5 volt.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Reference (1).

‡ *Ibid.*, (2).

† See Reference (1).

(2) The contacts are bridged by a very small drop of molten metal held in position by surface tension; the potential difference depends on electrode metal, current, and separation of contacts, but is normally about 2 volts.

(3) Arc. The potential difference is never below a minimum of about 14 volts, depending on the electrode metal, but may rise to much higher values.

(4) Spark. The minimum potential for this stage in air at normal pressures is 350 volts.

Stages 1 and 2 run into one another with no break, but the changes from stage 2 to 3 and from 3 to 4 are effected by the first stage becoming unstable and the voltage rising until the second stage can form and take its place; such processes are referred to as transition stages.

Each of these stages will now be discussed in detail, and the effect produced by the stage on the electrodes will be described.

Stage 1.

The maximum voltage rise between metal contacts due to decrease in pressure is always quite small and is usually of the order of 0·1 volt. It is probably greater for smaller currents because it is the energy expended at the contact which will determine when the metal will melt and result in the initiation of stage 2. The only effect on the electrodes is resistance heating which could lead to oxidation, but the duration of the stage is generally so short that the oxidation is negligible compared with that caused by subsequent phases.

Stage 2.

This commences when the heating due to stage 1 is sufficient to melt the point of contact of the electrodes. This phenomenon can most readily be observed by breaking a non-inductive circuit passing, say, 5 amperes and having an applied voltage of less than 14 volts so that no arc can occur. At each break of such a circuit a flash of light, which is emitted by the molten metal, is seen at the contact faces. An oscillographic record of the rise of voltage between tungsten contacts when breaking a current (see Fig. 1) shows a halt at about 2 volts after which the potential rises very rapidly to the applied voltage, or, if this is above 14 or the circuit is inductive, to the arc voltage. If platinum electrodes are used and the separation of them is made very slowly the molten bridge of metal can be obtained in a stable state and an investigation of its properties can readily be made. It is also possible to maintain the stable bridge between gold electrodes but for all other metals examined, namely tungsten, silver, and copper, no matter how slowly the contacts were separated the circuit broke suddenly with a single flash of light. It therefore appeared that the bridge was only stable between noble metals, the oxidation occurring for other metals resulting in its immediate destruction. The base metals were therefore enclosed in an atmosphere of hydrogen and the attempts repeated. The molten bridge was now found to be stable between tungsten electrodes but not between silver or copper even when currents as high as 25 amperes were used. A very interesting and at present inexplicable observation was that if one contact was tungsten and the other copper the bridge could be maintained in hydrogen, only when the tungsten was positive; a tungsten-silver pair did not give a stable bridge in either direction. There are several factors which can influence the stability of the bridge

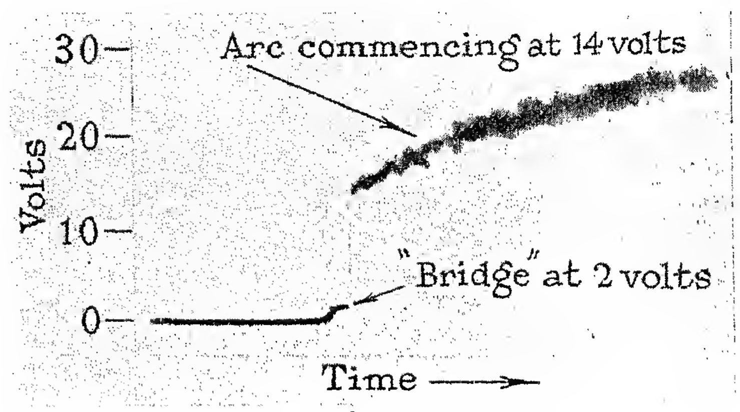

Fig. 1.—The break of an inductive circuit with tungsten points, showing stage 2 and the stable arc.

and which help to explain its instability between copper or silver electrodes. Chief of these are the high electrical and thermal conductivities of these metals. The former makes it such that little energy is expended at the final small area of contact, and the latter helps to conduct away this energy and to prevent rise of temperature. Against this the low melting points of these metals should help in the maintenance of the bridge. The surface tension of the molten metal is also of great importance.

The properties of the stable bridge between electrodes of platinum-iridium (25 per cent Ir) have been investi-

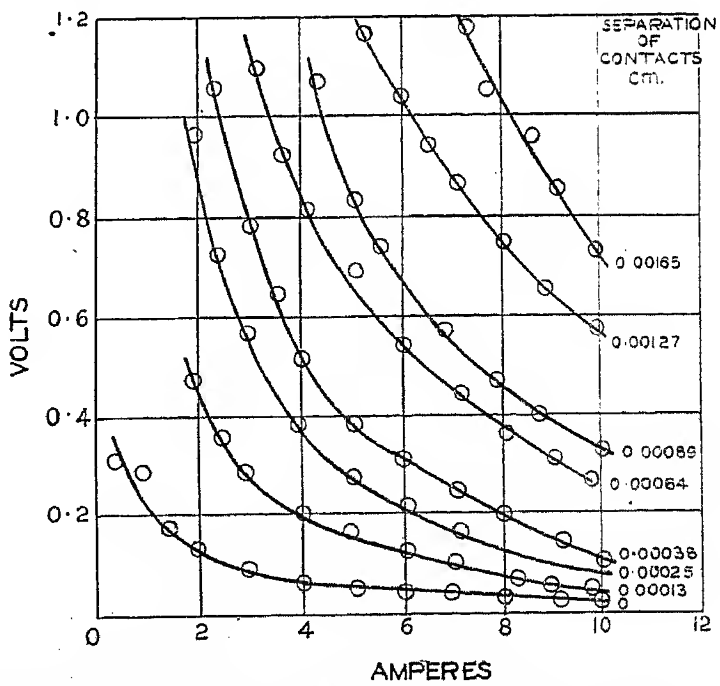

Fig. 2.—Characteristics for the molten bridge between Pt-Ir electrodes (25 % Ir).

gated in some detail, and these investigations will now be described. When these contacts, between which a current of about 5 amperes is passing, are very slowly separated, the potential difference rises gradually with the separation, and when it has reached about 0·7 volt emission of light commences. The voltage rises on further separation of the contacts to a maximum of about 1·5 volts, and on still further separation it becomes unsteady

and finally rises suddenly to the applied voltage with the breaking of the circuit. The maximum steady voltage attained is always about 1·5 volts and is independent of the current. The bridge of metal needs to be struck in the same manner as an arc, i.e. if the circuit is broken at another point the bridge collapses and can only be formed again by bringing the contacts together and separating them.

The relations existing between current, voltage, and separation of the contacts, were investigated by mounting contacts in such a way that the separation could be varied very slowly by a micrometer screw and measured to about $2{\cdot}5 \times 10^{-5}$ cm. The accuracy of these measurements is very difficult to estimate, since the contour of the contact faces can be changed quite considerably by the formation of the molten bridge and the heat produced is liable to cause distortion. The voltage/current curves obtained for constant separations are plotted in Fig. 2. Figs. 3 and 4, respectively, show the voltage plotted against the reciprocal of the current for given separations, and against the separation for given currents; since straight lines are obtained in each case the voltage is inversely proportional to the current and directly to the separation. This is a similar relationship to that found for the ordinary arc, the equation for which is of the form

$$V = \alpha + \beta l + \frac{\gamma + \delta l}{i}$$

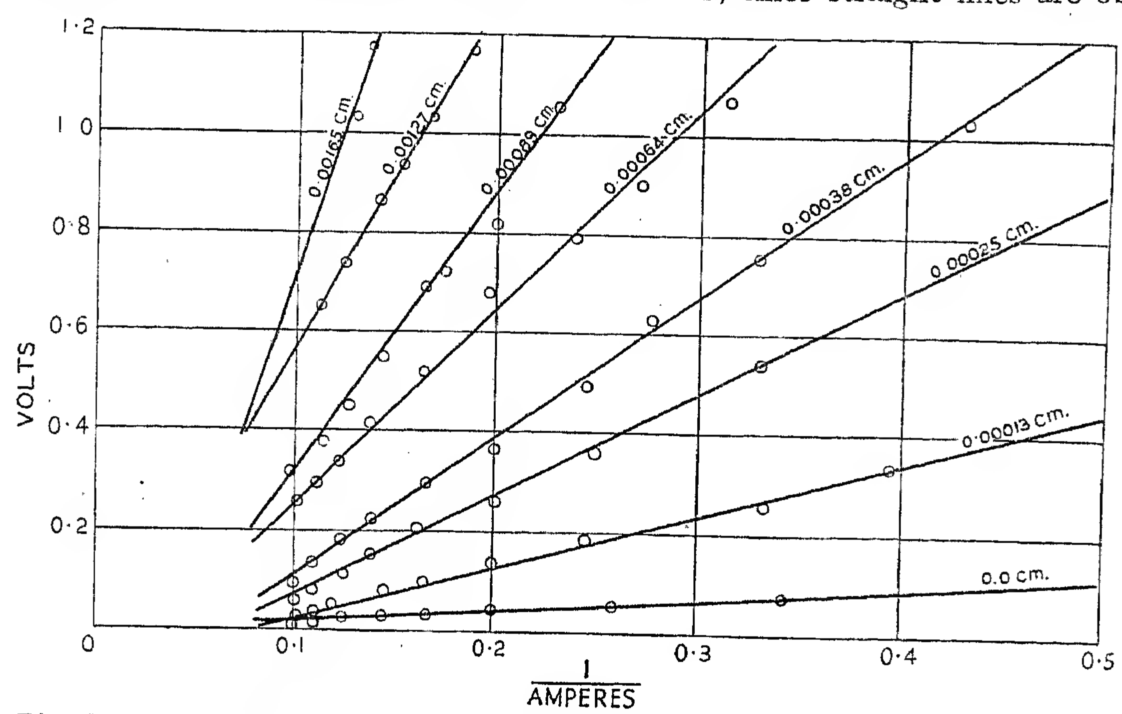

Fig. 3.—Characteristics for the molten bridge between Pt-Ir electrodes (25 % Ir).

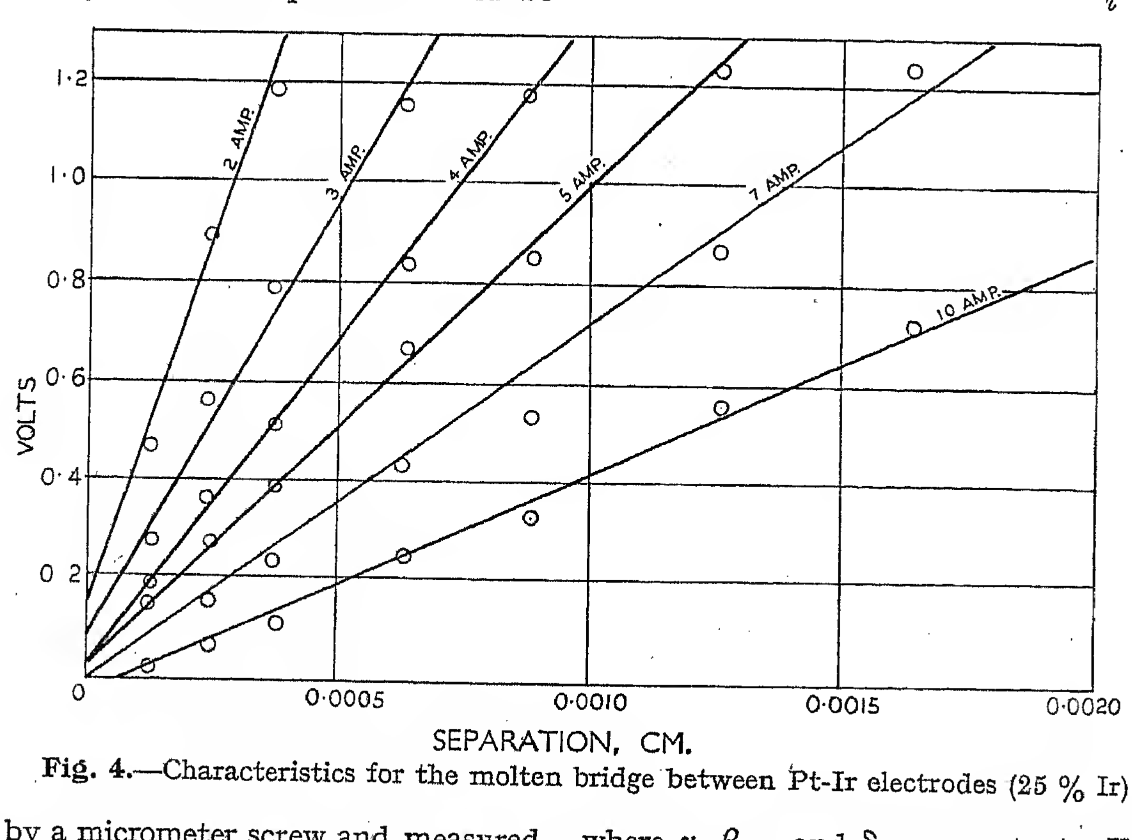

Fig. 4.—Characteristics for the molten bridge between Pt-Ir electrodes (25 % Ir).

where α, β, γ and δ are constants, V the voltage, l the separation of the electrodes, and i the current. From the results shown in Figs. 2, 3, and 4, the equation deduced for the molten bridge was as follows:—

$$V = -0{\cdot}061 - 165l + \frac{0{\cdot}357 + 5970l}{i}$$

Since some of the constants have negative signs this equation clearly cannot hold over the whole range of possible values of l and i, but reasonable agreement with the measured values is obtained for currents between 2 and 10 amperes and separations between 0·0001 and 0·0015 cm. It will be seen that the last constant, δ, is by far the most important in determining V, so that an approximate equation for the characteristics of the molten bridge is obtained by considering only this term, viz.:—

$$V = \frac{5970l}{i}$$

In view of the fact that the characteristics of this phenomenon are of a similar form to those for the ordinary arc, and that it needs to be struck, it was at first thought that a type of low-voltage arc was being examined. A photograph of the spectrum of the light emitted from the contacts was therefore taken in order to detect, if possible, the line spectrum of the contact metals. The spectrum was, however, continuous and therefore proved that the light was emitted by incandescent metal. A microscopic examination of the source of the light was made when a current of about 50 amperes was passing, which enables the separation of the contacts to be made as great as 0·01 cm. The source had the appearance of a drop of molten metal held in position between the contact faces by surface tension (Fig. 5). It was furthermore observed that the section of the incandescent liquid increased as the current increased, while its temperature decreased. A final proof that the contacts were bridged by molten metal was obtained by freezing the bridge in position by quenching it with a drop of water and immediately switching off the current. The solid bridge could then be very easily observed under the microscope and when small currents were passed through it Ohm's law was found to apply; with higher currents a deviation from the straight line of Ohm's law was found on account of heating (the bridge was eventually observed to become red-hot), and finally a point was reached at which the voltage suddenly commenced to fall with increasing current due to the bridge fusing and the characteristics of Fig. 2 coming into operation. Reduction of the current now caused the molten bridge to follow the usual course of becoming much hotter, unstable as the voltage reached 1·5, and finally breaking.

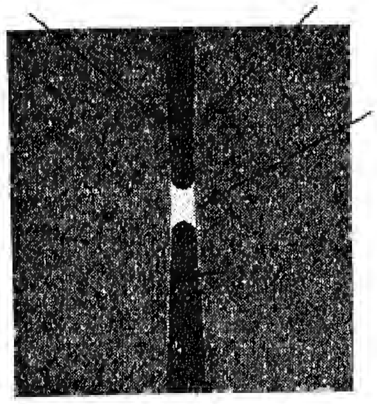

Fig. 5.—The molten bridge between Pt-Ir electrodes passing about 50 amperes. Magnification 30.

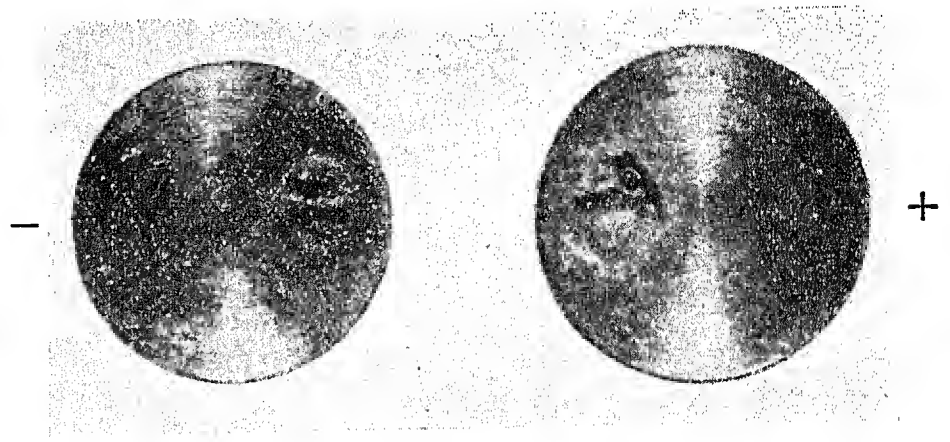

Fig. 6.—Transference produced on tungsten contacts by the molten bridge.

A further observation which at first seemed to support the theory that a type of arc was being dealt with was that if thin wires were used as electrodes the anode wire became red-hot while the cathode remained black. This can now be explained in terms of the Thomson effect, the necessary temperature gradient being that between the molten metal forming the bridge and the relatively cool electrodes. The difference in temperature of the two electrodes has a great effect in determining the direction of transference of the contact material and will be referred to later.

Although the authors conclude from the above observations that this phenomenon undoubtedly consists of a bridge of molten metal, no explanation of the voltage/current characteristics has been found. If we consider the approximate relationship

$$V = \frac{\delta l}{i}$$

we have that the resistance of the bridge is $\delta l/i^2$. Considering the bridge to be approximately a disc the resistance will be $\sigma l/s$, where s is the mean section and σ the specific resistance. Hence

$$\frac{\sigma l}{s} = \frac{\delta l}{i^2}$$

or s, the section, is proportional to the square of the current. It was observed under the microscope that the section did increase with increase of current, but measurements of the relationship were not made. Such a variation of section with current agrees with the observation that the temperature of the molten bridge falls with increase of current, for the energy Vi expended in the bridge, is approximately equal to δl, i.e. it is independent of current for a given separation. Hence on increasing the current the same energy will go to heat a larger mass of metal, giving consequently a lower temperature.

The fact that there is a maximum voltage which can be maintained across the bridge can be explained if we assume that the bridge becomes unstable when the ratio of length to radius exceeds a fixed amount. There is no evidence that this is so but it is probably the correct explanation. The value of this ratio calculated from the measured characteristics and the resistivity of platinum at its melting point is 4·3, and this is of the order which would be expected to cause instability.

As a consequence of the above observations the authors are convinced that this phenomenon consists of a drop of molten metal bridging the gap between the contact surfaces.

The effect of this molten bridge on the contacts is naturally small so long as it is maintained in a steady condition, as is possible with contacts of noble metals, only slight marking due to fusion being caused. But if a circuit carrying a current greater than about 2 amperes and with an applied voltage of less than 14 volts is made and broken by the contacts, localized transference from the anode to the cathode occurs, resulting in a pile forming on the cathode, with a corresponding pit on the anode (Fig. 6). The applied voltage must be less than 14 volts to prevent arcing, and there must be no inductance in the circuit for the same reason. It is found that if with such a circuit separate pairs of contacts are used to make and to break the current, transference occurs at both, but in general there is a good deal more at the make, about which more will be said later. The reason for the transference at break can be seen if we consider the process of formation and collapse of the molten bridge. As the contacts are separated the final area of contact becomes heated because of the rise of resistance, and the Thomson effect will cause the anode to become hotter than the cathode. Hence when the heating becomes sufficiently intense it is the anode which will melt and supply the metal to form the bridge. As the contacts separate further the bridge will eventually collapse, leaving some material on each contact, so that some of the metal of the anode which formed the bridge is transferred to the cathode. The amount of transferred material has been observed to increase with increasing current, as would be expected from the above explanation, but no quantitative measurements have been made.

A secondary effect may also be caused by this stage, for unless the contact metal is noble there will always be some oxidation as a consequence of the fusion of the metal, and this oxide can be very troublesome if it is insulating, for it tends to be probed to the bottom of the pit formed on the anode and to prevent the electrodes making good electrical contact, and for a similar reason any oil on the contact faces may be harmful as it may become oxidized and form an insulating film at the bottom of the crater.

Stage 3.

This is the normal arc which has been the subject of many previous investigations.

The conditions necessary for the formation of a stable arc at the break of contacts are that the current and voltage shall, during the process of break, cross the minimal arc characteristic.* It appears, however, from the authors' own investigations that an arc will occur at much lower currents than are given as the minimum values by other observers. For example, the minimal characteristic for tungsten determined by Anderson and Kretchmar† does not allow the formation of arcs with currents less than 1·75 amperes. But the oscillogram of Fig. 7 shows the break of a non-inductive circuit carrying 0·40 ampere at 200 volts, and arcing is seen to commence at 14 volts. The physical conditions which lead to the striking of an arc are that the voltage between the electrodes shall be greater than about 14, that the cathode shall be hot enough to emit electrons, and that the distance between the electrodes shall be small; it seems probable that the minimal characteristics only apply to stable arcs for which the energy input is sufficient to maintain the cathode at a sufficiently high temperature to emit electrons, while the arc illustrated in Fig. 7 is unstable and only persists so long as the electrodes remain hot from the previous stages of the break. The effect produced on the contacts is, however, the same, namely a vaporization of the contact surfaces over a fairly wide area and, with oxidizable materials, a deposition of oxide. There is little transference of material from one contact to another, and any that does occur is so widely diffused that it does not cause trouble. But perhaps the most important effect of the arc is that it burns away the pile produced on the cathode by the molten bridge which necessarily precedes the arc. The arc naturally strikes to the pile since it is the point of closest approach of the contacts, and it is burnt or vaporized away, leaving a uniform surface to the contact. If the amount of arcing is so adjusted that the burning is just sufficient to remove the pile without attacking to any extent the main part of the contacts, then the arc is of unqualified value. But excessive arcing causes the deposition of oxides which may form an insulating layer between the contacts. It is difficult, however, to control the stable arc sufficiently well to be able to adjust the burning to a satisfactory amount, and excessive oxidation usually occurs, but the unstable arc is more easily controlled and can be sufficient to completely remove any transference.

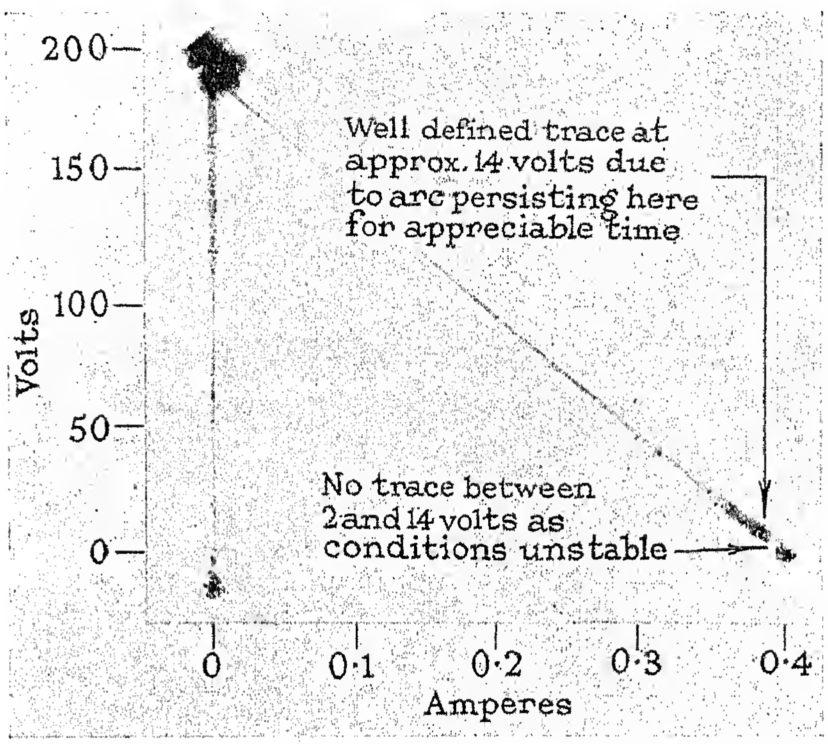

Fig. 7.—Arcing between tungsten contacts at the break of a non-inductive circuit carrying 0·4 amp. at 200 volts.

Stage 4.

The spark discharge occurs between contacts when the potential difference is greater than about 350 volts and the current is not high enough for an arc. It can either

* See Reference (3). † *Ibid.*, (7).

occur subsequent to an arc which has quenched owing to the conditions for its stability being passed, or it can occur without a stable arc having been struck if the initial current is small. In the first case the arc allows the contacts to separate to a reasonably large gap before the potential rises high enough for the spark to pass, and in such a case the only effect on the contacts is slight oxidation, if the contact metal is not noble, and general erosion of the cathode by the bombarding gas ions. The loss of material by the cathode is generally very slight and there is no transference on to the anode. But when the initial current is too small for a stable arc to strike, the spark commences very soon after metallic contact between the contacts ceases, and in such a case, in addition to any oxidation, transference from cathode to anode occurs due to a process analogous to sputtering in vacuum tubes, the material shot from the cathode by the bombarding gas ions falling on to the anode.

Transition Stages.

(1) When the molten bridge of stage 2 reaches unstable state, owing to the separation of the contacts, i will suddenly collapse under the forces of surface tension. The potential difference between the contacts is initially the maximum voltage for a stable bridge, namely about 2 volts, and the final voltage at break is that applied to the circuit, provided no arc strikes. If, however, the potential difference reaches 14 volts while there is still sufficient current passing, an arc will strike and will short-circuit the bridge. The potential difference therefore rises from 2 to 14 volts while the bridge is collapsing, and this forms the transition between stages 2 and 3. The time taken for the bridge to collapse is very small indeed and could not be resolved by an oscillographic observation of the variation of voltage with time. It is certainly less than 0·1 millisecond for a bridge between tungsten electrodes passing about 3 amperes.

(2) When contacts between which an arc is passing are separated, the arc will quench at a certain separation owing to the conditions for stability being passed, and the potential difference will then rise, either to the applied voltage with the complete break of the circuit, or, if the applied voltage is high enough, to the spark voltage for the gap. In each case, during the time that the voltage is rising from that of the stable arc, the current will be carried by the ionized gas and metal ions remaining from the arc, i.e. it will be in the form of an unstable arc, and the effects produced on the contacts will be similar to, and indistinguishable from, those of the preceding arc.

(3) In cases when a high voltage is applied and the current initially passing through the contacts is too low for a stable arc to strike on break, the processes will be similar to the above but the effects will be different. At the collapse of the molten bridge, which will be very short for small currents, an unstable arc will strike at 14 volts and will very quickly quench because the energy input is insufficient to maintain it. But sufficient ionization of the gas has taken place for conduction to occur as the voltage rises from 14 to the applied voltage, and since the gap between the electrodes is still small the gaseous conduction will cause sputtering of the material of the cathode, which will transfer on to the anode. This process of sputtering is exactly the same as that occurring with a true spark, but in the case of the transition stage it occurs with a lower potential between the contacts—the conducting ions being those remaining from the short-lived unstable arc. Although this has been called a transition stage, if the applied voltage is insufficient for a true spark to form the stage will still occur and will last until the current has fallen to zero and the circuit is completely broken; thus transference from cathode to anode by sputtering can be produced by applied voltages much less than the minimum sparking voltage of 350, and has in fact been observed with a voltage of only 30. The necessary conditions are that the voltage shall rise high enough for an unstable arc to form in order to supply the conducting ions, and that the arc shall immediately quench so that the gap between the electrodes is not too large for the material sputtered from the cathode to reach the anode. This rapid quench occurs only when the initial current is too small for a stable arc to form, i.e. usually less than about 1·5 amperes.

THE DESTRUCTIVE EFFECTS ON THE CONTACTS

The stages which can occur at the break of a circuit have now been described individually, and we are in a position to consider the effects produced on contacts which are making and breaking circuits of different types.

On the mutual approach of two contacts between which a potential difference exists, unless that potential difference is above the minimum sparking voltage of 350 the current which passes before metallic contact is made is very small indeed.* At the first contact of metal, however, a current will flow, and if, as we will assume for the moment, the circuit is non-inductive, the current will immediately rise to its final value and the energy expended will result in the fusion of a very small portion of the positive contact, which is hotter than the negative on account of the Thomson effect, and stage 2 will thus be initiated. If the current is high enough the bridge will remain in being while the contacts continue to close, until it eventually freezes, subsequent separation of the contacts will break the minute weld, and by leaving a portion of the weld metal (supplied by the anode) on each contact it will result in transference from anode to cathode. If, however, the current is too small to maintain a stable molten bridge across the gap between the electrode faces at which contact first occurs, the contact being due to prominences, the metal will be fused and metallic contact will cease; the low current, furthermore, precludes the formation of a stable arc so that the transition stage (3) will take effect, and if the voltage is high enough transference from cathode to anode will occur.

The foregoing applies to contacts which come together quite slowly; usually, however, the " make " of a circuit is not quite so simple because at even moderate speeds of approach several bounces apart of the electrodes can occur before final contact is made (Fig. 8).

For the moment we will pass over these bounces and consider the break of the contacts. Stages 1 and 2 will occur for all contacts as described previously, resulting in oxidation and, on the collapse of the molten bridge, transference from anode to cathode—the amount of transference being greater for larger currents. If now the applied voltage is less than 14 no further stages will occur

* See Reference (5).

and the transference will remain. But if the voltage is greater than 14 the minimal arcing characteristic may be cut and a stable arc will strike, which will tend to remove by oxidation and vaporization the pit and pile previously formed. The extent of the arcing will depend on the current and voltage applied to the circuit; slight arcing will not completely remove the transference, while intensive arcing will cause a good deal of oxidation and rapid vaporization of the contacts. If the minimal characteristic is not cut only a slight amount of unstable arcing will occur, and then the transition stage (3) will come into being, resulting in transference from cathode to anode. If the voltage is sufficiently high the spark stage will occur whatever the value of the initial current, and will give rise to oxidation in addition to that caused by previous stages. Further transference from cathode to anode may take place if the current is small enough for the spark to form while the separation of the contacts is still small.

Referring again to " bouncing," this can be of various degrees of intensity, the worst cases resulting in the com-

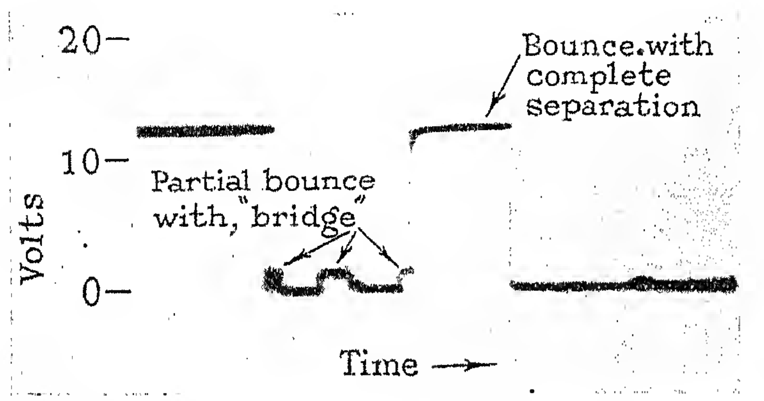

Fig. 8.—Bouncing at the " make " of tungsten contacts.

plete break of the current and the lesser ones only opening the contacts sufficiently to cause one or more of the stages of break to be formed and then closing again. The oscillogram shown in Fig. 8 is of a case in which the first bounce breaks the current as far as stage 2 and the second bounce completely breaks the circuit; very small bounces follow this until complete contact is made. Bounces with currents greater than 2 amperes most frequently result in the formation of stage 2 and then a remake. Such a process is found to cause a great deal more transference from anode to cathode than complete makes and breaks, and the greatest part of the transference occurring with rapidly operated contacts can be put down to this cause. Transference at make or bounce can be explained in a similar manner to that occurring at break; a molten bridge is formed which consists mainly (owing to the Thomson effect) of metal from the anode, and as the contacts come together the energy expended at the bridge is reduced until it finally freezes. When the contacts are separated again the solid metal of the bridge is left partly adhering to the anode and partly to the cathode, so that transference from anode to cathode has occurred. Hence whenever a molten bridge is formed the metal for the bridge is drawn from the anode, and when it is extinguished, either through separation or approach of the contacts, the metal is shared between anode and cathode. Each bounce occurring at make will therefore cause further transference and in practical cases will lead to the make of such a circuit being more destructive than the break.

So far only non-inductive circuits have been dealt with as these are the simplest to consider, for the current/voltage relation for the contacts is a straight line

$$e = E - Ri$$

where e and i are the contact voltage and current, E is the applied voltage, and R the resistance of the circuit. The path followed is therefore completely defined by the applied voltage and the initial current. The presence of inductance in the circuit makes the effective voltage uncertain at any instant during the make or break of the current, unless the contact points are shunted by a resistance. In the latter case, if we assume the total current through the circuit to remain constant during the process of break, and if r be the resistance of the contact shunt, i_s the shunt current, and i_c the contact current, then

$$e = ri_s = r(i_0 - i_c) = ri_0 - ri_c.$$

This is identical in form to the relationship for a non-inductive circuit, and hence the contacts will behave as if they were breaking a non-inductive circuit with applied voltage ri_0 and initial current i_0. The process of make will be similar but the voltage and current will then be ri_s and i_s respectively, i_s being the shunt current when the contacts are open. The magnitude of the inductance only has effect in that it controls the rate at which the voltage/current characteristic is traversed, and this affects the amount of destruction due to each phase. But the transference due to stage 2 is related only to the number of makes and breaks for a given current and hence is independent of inductance, while the burning due to arc and spark is a function also of time and will be increased by increase of inductance.

For an inductive circuit in which the contacts are not shunted the degree of destruction at make will be inversely related to the inductance, for the higher the inductance the greater the chance of all bouncing having ceased before the current has attained a dangerous value. At the break of the circuit stages 1 and 2 will be followed as usual, since the current change due to these stages is normally small and hence little inductive voltage will be generated. But at the collapse of stage 2 the current will tend to fall, the voltage will rise immediately, causing the arc characteristic to be cut, and a stable arc will strike. This will persist until the conditions for stability are passed owing to increasing contact gap and reduction of the energy supplied by the inductance, after which the voltage will further rise to the spark stage, which will eventually quench owing to complete exhaustion of the stored energy. The combined effect of make and break will therefore be transference from anode to cathode, which will be greater for smaller inductances, and oxidation and vaporization which will be greater for larger inductances, and, depending on its amount, will reduce or entirely remove the transference.

It is general in the breaking of inductive circuits to place a condenser across the contacts, in order to reduce the arcing and sparking at break. The effect of the con-

denser is to take current from the contact points as soon as the voltage between the points tends to rise, and thus to prevent or delay the attainment of the conditions necessary for the formation of the different stages of the break. The condenser has no effect on stages 1 and 2, which are formed with very small increases of voltage, and hence the transference from anode to cathode and slight oxidation due to these stages will still occur. If now the condenser is of high enough capacitance to suppress completely any further stages, the circuit will break at a low voltage and this transference will remain. It is therefore desirable to arrange that the condenser is of such a value as to allow a small amount of arcing to occur which will remove this transference and preserve a uniform surface on the electrodes. The presence of a condenser also has an effect at the make of a circuit, for during the open period it becomes charged to the applied potential and on make of the contacts it will discharge through them; this results in the fusion of the first point of contact, but the bridge immediately collapses owing to the discharge current being only a pulse, and the discharged condenser prevents there being a voltage rise to maintain any gaseous discharge between the points. The material of the collapsed bridge is oxidized and scattered on the electrode surfaces about the point of contact; it is probably the violence of the discharge that causes the bridge to collapse in this manner instead of leaving localized transference as occurs at a normal break.

CONCLUSIONS

The foregoing observations lead to the following suggestions for the prevention or reduction of contact-point wear. In the first place the material of which the points are made should, in order to reduce transference due to the molten bridge, have as high a melting point as possible, particularly if currents greater than 2 amperes are to be dealt with. High electrical and thermal conductivity will also help in this. A material which is not readily oxidizable should also be chosen if possible.

These are the only points with regard to the contact material which need be considered if the applied voltage is to be less than 12 or 14 and the circuit is non-inductive, as then arcing cannot occur. If the voltage is liable to rise higher than the arcing voltage, the melting point of the material becomes of still greater importance for the reduction of vaporization. Considering the conditions of the electrical circuit, a current of about 1·5 amperes should always be aimed at if possible, as then the two directions of transference tend to counteract each other and only a very small amount of arcing serves to keep the contacts in good condition. For higher currents more arcing must be allowed in order to remove the increasing amount of transference from anode to cathode. For currents lower than 1·5 amperes the applied voltage should be kept as low as possible in order to reduce transference from cathode to anode. The amount of arcing is of course controllable by variation of the inductance and capacitance. In addition to these measures the greatest care must be taken to reduce to a minimum bouncing of the contacts at make by careful design of the operating mechanism and of the contact supports.

In conclusion it should be remarked that although new facts came to light during this investigation, there are still a number not fully understood, in particular the mechanism of transference. Explanations have been put forward for this and they appear logical, but they are conjectural only, as there are no conclusive proofs that they are correct.

ACKNOWLEDGMENTS

This work was carried out in the research laboratories of Messrs. Joseph Lucas, Ltd., and thanks are due to the directors of the firm for permission to publish the results. The authors must also thank Mr. E. A. Watson, O.B.E., M.Sc., Member, for much helpful advice during the course of the work.

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DISCUSSION ON "STREET TRAFFIC SIGNALS, WITH PARTICULAR REFERENCE TO VEHICLE ACTUATION"*

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 15TH DECEMBER, 1937†

Mr. F. H. Whysall: It is interesting to recall that in Northern Ireland the number of private motor-cars in use in 1922 was 4 542, whereas to-day there are 33 000.

Traffic signals on new arterial roads are a mistake; they have been made necessary by "ribbon building." Traffic can be accelerated by the construction of main roads with fly-over bridges, the cross-roads being carried underneath.

In Belfast there are 12 fixed-time-cycle and 11 vehicle-actuated traffic signals. I prefer the latter, as they avoid delay in giving right-of-way.

Mr. E. N. Cunliffe: Most people are now agreed that in general the vehicle-actuated signals form a better system than the older fixed-time-cycle signals, and are often superior to a system of police control, particularly where the volume of traffic at the crossing is very heavy and the type of crossing complicated. This superiority, however, is not so marked, and indeed may not be present at all, in the case of isolated intersections where the traffic on the main road is very heavy and the traffic on the cross-road is light and intermittent. In one type of crossing that I have in mind there would probably be as much delay if vehicle-actuated signals were installed as if the crossing were police-controlled. This seems to be due to the fact that the traffic on the side road, although comparatively very light, creates demands and secures its minimum green periods with such frequency as to obtain more than its fair share of right-of-way, at the expense of the heavy main-road traffic. From the author's explanation of the working of vehicle-actuated signals it will be seen that first of all there is a minimum green period for all traffic, which ensures that any vehicle coming up the side road and creating a demand will have a minimum period of safety in which to cross. If only a single bicycle comes along it has the effect of holding up the traffic on the main road for the duration of the minimum green period. Would it not be possible to arrange for some counting method on the side road which would take into account the number and frequency of vehicles arriving and creating demands, so that in the case of one vehicle arriving a much longer waiting period would be provided than if a number of vehicles arrived more or less together? Such a modification would speed up the traffic on the main road very considerably.

Another type of intersection to which I should like to refer is the one where there is a big preponderance of traffic turning right. In order that such traffic may clear itself it is usual to provide an early cut-off for the opposite stream of traffic. Experience shows, however, that at the commencement of the phase in question the right-turning traffic can very often get in first and prevent entirely the clearance of the opposing stream of traffic. I think, therefore, that in practically every case it is better to provide an early start as well as an early cut-off for the straight-through traffic. I should be interested to know whether this coincides with the author's views on the subject.

The apparatus used to control vehicle-actuated signals appears to be quite reliable, but the type of wiring used is very flimsy when compared with the small wiring associated with other electrical plant. The insulation seems thin and unprotected, especially in view of the fact that it is intended for service in street pillars exposed to the weather. I should be glad if the author could say whether any trouble has been experienced in this connection.

Mr. J. McC. Barry: There is one point that has interested me in connection with the telephone relays employed in traffic-control equipment, and that is the possibility that the switches controlling the lights may get out of sequence. This sort of thing happens in lift controllers, and may cause "up-and-down" running almost endlessly. This can be put right by pulling out the control-panel circuit-breaker, the remaking of which automatically brings about the proper resetting of the sequence relays. Is there some similar means of providing for the possibility of out-of-sequence of the switches controlling traffic lights?

Mr. J. A. Hind: I understand from the paper that the detector pads can only work in one direction owing to interlocking of the bellows, but that when a vehicle passes over a pad in the correct direction both sets of bellows operate, thereby giving the speed of the vehicle as well as registering a demand for right-of-way. Is this so?

Captain G. M. Nelson: In the first place I should like to make comparisons between fixed-time-cycle signals and the vehicle-actuated system. Most traffic authorities are agreed that the fixed-time-cycle signal serves the purpose where the traffic is dense and fluctuates little from day to day. But where the traffic is intermittent, as in Belfast, it is much harder to control, not only from the motorist's standpoint but from the pedestrian's. Dense traffic is such that the pedestrian cannot cross the street otherwise than at right angles: in intermittent traffic the pedestrian can cross any way he likes, if he takes a risk.

Automatic signals were primarily conceived for traffic crossing at right angles: they were never intended to cater for traffic which turns or "filters." I still think that the mechanically controlled signal is inefficient in this respect. The only way to overcome the difficulty would be to construct loop roads to by-pass busy junctions. This is out of the question in large built-up cities, but is

* Paper by Mr. F. G. Tyack (see page 125).
† Joint Meeting with the Belfast Association of Engineers.

still possible in new areas, particularly rural areas. I believe that the pedestrian trouble would thus be solved easily and expeditiously. While turning is permitted we have to sacrifice the speed of the traffic and bring in a device which will take away some normal vehicular cycle of the signal. If we insist on pedestrians being catered for at busy road junctions, and do not force them to use subways, as is done in various large cities, vehicular traffic in part must be sacrificed.

In the future, traffic control will probably be incorporated in a new system of street lighting, particularly in suburban and rural areas. Street lighting will be diffused across the highways from the kerb, and coloured signal lights will be treated in the same manner by throwing across a beam of light—green, amber, or red—to a width visible to road users from a distance of, say, 50 yards. This could be done by means of the fixed-time principle, the vehicle-actuated principle, or an invisible ray. Such a system would do away with a great many of the pillars and posts which now have to be put up for the control of traffic and are, in my opinion, a distraction to the motorist.

Mr. Whysall mentioned that the use of traffic signals can be avoided by providing new routes. This is precisely what the traffic authorities are aiming at. They want motorists to use other routes so as to mitigate congestion at main street junctions.

The author demonstrated the colour used for turning traffic, and we have a very good example of this in front of the Belfast City Hall. It was found that traffic coming from Chichester Street to Donegal Place would require longer to negotiate a right-hand curve than traffic which filtered to the left into Donegal Place The manufacturers provided a cut-off of 5 sec. in order that the turning traffic on the wider arc might get clear, and added 5 sec. more to get traffic clear when rounding the corner from Chichester Street. There will be a further example of this at Castle Junction when the layout has been completed.

For traffic which in certain circumstances is permitted to filter or to turn to the left the best expedient is the green arrow. This gives the right-of-way to all filtering traffic when the red light is showing and holding up through traffic, but it does not operate if a "Cross now" phase is functioning.

With regard to the all-red phase, this works very well in the absence of a "Cross-now" phase, holding up traffic for a period of 10 or 15 sec. in order to give confidence to pedestrians who wish to cross. In many ways I think the all-red hold-up is preferable to the crossing phase.

Mr. Alexander Brown: One weakness of traffic signals is the fact that they enable the motorist to turn to the right. The author's demonstration of his model traffic-control system leads me to visualize a smash-up every time traffic attempts to turn to the right on a crossing. It seems to me that if right-hand turns were prohibited a great deal of danger and confusion would be avoided.

[The author's reply to this discussion will be found on page 635.]

IRISH CENTRE, AT DUBLIN, 16TH DECEMBER, 1937

Mr. S. T. Robinson: It is interesting to recall that traffic lights were in operation some years ago at Buenos Aires, and though they were apparently operating efficiently they were later replaced by policemen.

Lieut.-Col. H. E. O'Brien: One of the difficulties in connection with the design of traffic signals is our lack of pre-knowledge of what traffic is going to do. Imagine a large group of vehicles passing from Oxford Circus to Piccadilly Circus: no one knows how or when it will arrive, and what right-of-way time it will require on arrival.

Dublin has no serious traffic problem compared with London or large provincial towns, and it has only one place where the congestion is very bad—opposite Trinity College (College Green). Nevertheless, signals would help if adopted generally in Dublin, especially if used in combination with gyratory systems. What is the author's opinion of such combinations of signals and gyratory systems, e.g. that at Piccadilly Circus?

Col. S. W. Carty: With regard to the large central traffic-control panels in Chicago, can the police alter the system according to the time of day or the density of the traffic? Such a system exists at Amsterdam, and would appear to have great advantages.

It appears to be left to each local authority to decide whether left-hand filtration is permitted or not. Could green arrows be fitted to the traffic lights at Merrion Square, Dublin?

Mr. Norman Chance: The flexibility of the vehicle-actuated signals installed at Merrion Square, Dublin, is very great. Co-ordinated systems, however, have their limitations. It was originally intended to install such a system at the two ends of Butt Bridge and at Abbey Street and Beresford Place; the limitations in this case were due to slow-moving vehicles. A firm of contractors submitted a time-and-distance diagram, but admitted that it was not satisfactory. A proposal was considered to install close to the kerbs special detectors for slow-moving vehicles, but this did not cater for right-turning traffic.

Horse-drawn vehicles have always formed an important part of Dublin traffic, and are present even on the central artery formed by Westmorland Street and O'Connell Street.

Mr. G. Brennan: Dublin's first light signals, erected in August, 1937, are of the latest vehicle-actuated pattern. They have proved their efficiency to the traffic authorities and, as far as we can learn, to the great majority of road users. The signals have speeded up traffic without affecting safety, and drivers in general have quickly adapted themselves to the new system. No serious accident has occurred since the signals were erected.

The standard traffic-control signals do not cater sufficiently for pedestrians at junctions where pedestrian traffic is heavy. Pedestrians approaching a junction on the left footway, once they have passed the primary signal on that side, have no signal directly facing them to guide them. They have to look in a diagonal direction

to the secondary signal on their right, a practice which is attended with danger. The pedestrians approaching on the right footway are in a better position, as they have a signal directly in their line of vision. It may be that the ideal solution is the provision of a pedestrian crossing demarcated by illuminated road-studs, illuminated in phase with the main signals. This is being experimented with in Paris, where the idea of special crossings for pedestrians originated.

As regards the problem of right-hand turnings carrying a large amount of traffic, if the signal engineers cannot provide a solution it may be necessary for the traffic authorities to consider altering the routing of traffic so as to reduce right-hand turning as far as possible.

I should like to ask the author what is the maximum spacing which may exist between intermediate junctions before the interconnected or flexible progressive system can be applied.

Mr. E. C. Bredin: Where traffic lights are installed, does traffic congestion result from people not knowing which way to go, and stopping to find out when they are in the centres of road junctions? Under present conditions such people could ask the police officer.

Where the early cut-off facility is provided, how does the driver having the extended period know that the opposite traffic is stopped, and that he may turn right in safety?

At some T-junctions, as at the Nassau Street end of Dawson Street, Dublin, there is insufficient room to segregate the traffic so as to permit straight-through traffic to continue to flow while right-turning traffic is held up. How is it proposed to overcome this difficulty?

Mr. C. R. H. Stewart: When street traffic signals are in operation it is particularly important that vehicles should be able to start and stop when required. Road surfaces are very slippery in Dublin, whereas in London the road surfaces are good and the sanding organization is efficient.

I recommend the use of the cinema for educating road users in methods of ensuring safety on the roads. At present, people approach intersections in the wrong parts of the roads. Driving tests in England have done much to obviate this practice.

Further to Mr. Chance's remarks on the problem of Butt Bridge, it was found there that 40 % of the total traffic was horse-drawn, at a speed of only 2·5 m.p.h. The installation of traffic signals should have the effect of reducing the volume of horse-drawn traffic, so resulting in a general improvement in traffic conditions.

At Merrion Square the changing of the stopping-places of public service vehicles has been most advantageous, and similar changes should be made at many other junctions, whether signals are installed or not. "Islands" would appear to be desirable for the use of pedestrians.

I should like to ask the author whether photo-electric cells could be used to detect drivers who disobey traffic signals.

Mr. E. N. Allan: What are the effects of variations in voltage on the timing of the controller?

Does the author's system provide for satisfactory regulation of the traffic in the event of a power failure?

Traffic signals do not appear to make adequate provision for pedestrians, particularly where turning traffic is concerned.

Mr. B. J. McCaffery: Why are traffic signals designed particularly for vehicular traffic? Can no special provision be made for pedestrian traffic?

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, BIRMINGHAM, MANCHESTER, BELFAST, AND DUBLIN

Mr. F. G. Tyack (*in reply*): I have classified my reply into subjects and have arranged these as far as possible in the same order as in the paper.

Standardization.

The desirability of standardization of terminology cannot be over-emphasized. It is hoped that in the near future a language, which all those concerned with traffic control may understand and talk, will mutually be agreed, at least in the United Kingdom.

The term which is subject to most confusion is "phase." Until the last few years signals were largely confined to straightforward cross-roads, signalling schemes for more complex junctions being very much the exception. The controllers were described as "two-phase." The timing switches which controlled the durations of the parts of the cycle were marked as applying to "phase A" and "phase B," and also the signals and detectors were cabled to "phase A" and "phase B" terminals. It was not realized that the timing switches were not directly associated with the signals, and it was not until complex signalling schemes were common that the distinction became apparent. Some people then regarded "phase" as being associated with the timing switches and the distinct traffic conditions, and others associated it with the groups of signals, traffic lanes, detectors, cables, and terminals. Non-technical people, not being concerned with the detail of traffic controllers further than the timing switches, generally fell into the former category. Engineers, who had to design and install the equipment, found the need for two discriminating terms, and generally fell into the second category, using some other term such as "cycle-part" or "stage" to indicate the condition of all the signals or of all the traffic at any one time. Dictionaries show that both uses of the word "phase" are quite correct (cf. "phases" of the moon, and electrical "phases"), and until use of the term has been confined to one or other of the meanings misunderstandings are bound to occur.

Provision was made in 1933* for standardization in the outward appearance of signals, the order in which the various indications were to be displayed to drivers, the general performance of fixed-time signals, and several other basic respects. Up to the present, however, there has been no standardization between manufacturers of the apparatus comprising the controllers, and although the vehicle-actuated controllers on the market to a large extent provide similar facilities there is not, as yet, any standard specification covering the mode of operation.

* See Bibliography, (14).

Mr. Trigg advocates the term "All Red" in preference to "Overlapping Red." This is a good example of one facility named differently by different manufacturers, and it is hoped that standardization on one term or the other will be effected in the near future.

Mr. Cowley suggests that standardization of the lamp sequence in this country has not yet been effected. The sequence should invariably be as set out on page 126, and any installation not following this sequence must be out of order. A possible cause of amber appearing alone before green is the burning-out of the red lamp.

Types of signals.

I am grateful to Mr. Taylor, who is an authority on traffic matters, for his views on portable and suspended signals. It is gratifying to learn that colour-light signals have been approved for use at temporary obstructions, though, owing to lack of power, it will not be possible to use this type universally. This and the information on page 125 answer Mr. Strickland's question.

Mr. Marsh draws attention to two methods of traffic control which are not mentioned in the paper, but both suffer from disadvantages which preclude them from modern practice. The first—a single projector with moving coloured spectacles—is the "searchlight" signal used on railways. With this it is impossible to show any two colours simultaneously (e.g. red with amber, or green with amber), and without elaborate proving circuits it is not possible to guarantee that the mechanism of one or other of the signals might not fail and cause conflicting indications. The second method has all the disadvantages of ordinary human control, among which may be mentioned fatigue, non-impartial discrimination, difficulty of co-ordination, cost of labour and provision of horse, and danger to the policeman and horse; and in addition the lack of clarity of the indications (no distinction between the two change-over indications, and no "stop" indication at all), noise (the whistle would be blown every few seconds throughout the day), and the impossibility of applying the principle to multi-phase control schemes.

In reply to Mr. Marsh's question as to why audible signals are not used I would say, first of all, that there would be the continual nuisance to people near such signals, both by day and by night. In addition, audible signals could not be made to apply to selected roads only, nor could they give continuous "stop" indications. In short, there does not appear to be any reason why such signals should be used in preference to colour-light signals.

Mr. Binns comments on the fact that signals vary in shape and size in different localities. Signal construction is closely defined in B.S.S. No. 505, with which all signals installed since 1934 have had to comply. The only variations are signals installed before this time. A common variation is the use of 12-in. lenses in place of 8-in. lenses.

I have heard a complaint that, owing to the number of coloured lights in the streets, traffic signals can be missed; and the use of position-light signals has been suggested for all traffic. Apart from the fact that the concentrated illumination of modern signals renders such signals readily distinguishable, the great preponderance of white lights in the streets would make position-light signals more difficult to pick out than colour-light signals.

Siting of signals.

The siting of signals would appear to be subject to much controversy, and present practice has been criticized during the discussions. Opinions of those with first-hand experience indicate that suspended signals alone are not satisfactory, while, on the other hand, several speakers have suggested that post-mounted signals are liable to obstruction. Some speakers have advocated suspended and central island signals, while others have suggested totally different forms of signals, such as illuminated road-studs and kerbstone lights which would produce a diffused coloured effect in the atmosphere.

In my opinion there is no reason why present practice should not be entirely satisfactory, provided sufficient signals are installed. There should not be less than two signals for each road (on account of possible burning-out of lamps, apart from obstruction) and, where space permits, third and even fourth faces should be installed on islands, etc. There have recently been numerous cases of such extra signals being added to old installations (a notable example is Oxford Street, London) and other junctions where signals are liable to obstruction should be treated similarly.

Apropos the remark by Mr. McKinnon that suspended signals in Copenhagen were not satisfactory, I would say that in the case of a recent installation in Denmark the method suggested by Mr. Borlase Matthews—suspended signals—has been employed.

The method of diffused lighting suggested by Capt. Nelson would present several practical difficulties, among which are obstruction of the light by mud and vehicles, and the necessity for some dense vapour or cloud in the atmosphere to enable the colours to be seen.

Phantom indications.

Three speakers comment on difficulties experienced by drivers when the sun, shining directly on to signal lenses, causes the lenses to have the appearance of all being illuminated at once. This effect, which is technically known as "phantom," is most undesirable, and the speakers should report the particular cases with which they are conversant to the responsible bodies so that the matter can be rectified. I would also draw attention to my remarks on page 127 of the paper.

Time indicator signals.

Mr. Graham of Birmingham and also several others advocate time-indicator signals. It is satisfying to me that such suggestions come from areas which abound with fixed-time signals, and that none come from areas where vehicle-actuated signals predominate. There could be no clearer demonstration that road users in the former areas have unfortunate experiences of arbitrary interruption and unnecessary hold-ups at fixed-time signals, and that they seek some more efficient arrangement.

With vehicle-actuation, time indicators are fundamentally not applicable and not necessary, and they could even be described as undesirable.

Consider the following examples:—

(*a*) An empty junction, with a vehicle approaching a red signal and just about to cross a detector. The time during which the signals on the road having right-of-way will remain green is clearly zero, though no person or machine could have predicted the precise instant when this change would take place.

(*b*) A junction with no traffic approaching the red signals. Here again no person or machine can predict how long the green indication will persist. It might show for several hours (e.g. during the middle of the night) and in the limiting case would persist indefinitely.

(*c*) A junction at which a vehicle has just traversed a detector in a road having right-of-way and at which a vehicle is just about to traverse a detector in a road not having right-of-way. In this case the green persists sufficiently long to cover the passage of the first vehicle past the stop line at the speed at which it is travelling.

Examples (*a*) and (*b*) demonstrate the inapplicability of time indicators to vehicle-actuated systems, and example (*c*) shows that vehicle-actuated systems provide something which is very much superior.

Discerning drivers have a greater sense of security where vehicle-actuated signals are used than where fixed-time signals are used, even when the latter incorporate time indicators, as normally they are assured of sufficient green period when they have once traversed a detector.

Mr. Graham argues that drivers can be caught unawares even at vehicle-actuated intersections. Vehicle-actuated controllers normally remove the green indication only in the absence of traffic, and even on operation of the maximum timer (due either to the necessity of interrupting a continuous stream of traffic or to the over-riding control of a stream of traffic proceeding in accordance with a progressive plan) the state of affairs is not so serious as might appear at first sight. The 3-sec. amber period protects a vehicle travelling at 15 m.p.h. for 66 ft., or at 30 m.p.h. for 132 ft., from the point where the vehicle is at the time when the green indication is removed until right-of-way is given to opposing traffic, so that even if a driver is so close to the stop line that he cannot stop in safety when the amber indication appears he is still adequately protected. Violent braking is dangerous and is not required. The amber indication has the same force as a point-duty policeman holding up his hand and stopping the third or fourth vehicle back and not the one nearest to him.

Finally, fixed-time signals generally, and the time indicator variety in particular, have the serious disadvantage that they give rise to dangerously high speeds in efforts to " beat " the signals during the amount of green period which drivers know to remain.

Filtration—Green arrows.

Several speakers refer to the green-arrow indications which are described on pages 126 and 127. Such indications are only used sparingly, as they rob pedestrians of their opportunities to commence crossing and may affect the flow of the traffic in the phase having right-of-way.

As Capt. Nelson says, green arrows must be extinguished during pedestrian " Cross now " periods.

In reply to Col. Carty, there is no technical reason why green arrows could not be fitted to the signals at Merrion Square (Dublin). The question as to whether green arrows are desirable or not rests with the traffic authorities.

Pedestrians.

The problem of pedestrians appears to have caused lively discussion, though in one case it is suggested that reference to pedestrian traffic may be irrelevant as the title of the paper refers particularly to vehicle-actuation. The term " vehicle-actuation " is of long standing, but it would probably be less misleading if " traffic-actuation " were substituted, " traffic " being construed to include pedestrians. The Ministry of Transport pedestrian scheme is described in paragraphs (*a*) to (*d*) on page 127, while on page 137 the most suitable type of multiphase controller is indicated.

It does not appear to be generally realized that in no circumstance is a driver justified in running down a pedestrian, or that drivers must always give way to pedestrians on pedestrian crossings, or that pedestrians must not rely solely on any signals except those bearing the words " Cross now."

Mr. Kennett suggests side-vision signals for the assistance of pedestrians. Such signals are used on railways; but on roads, with conflicting streams of traffic at wide angles to one another, there would be too much risk of confusion. Furthermore, a pedestrian who has commenced to cross a road should not watch signals but the traffic.

Mr. Ritter complains that there are dangers for pedestrians even when " Cross now " signals are used, on account of the time necessary for traffic to clear and the fact that right-of-way may suddenly be transferred from the pedestrians to one of the vehicular phases when the pedestrians are in the middle of the road. The former difficulty may be overcome by use of an overlapping red clearing period immediately prior to illumination of the " Cross now " signals, while in the latter case it should be explained that a minimum clearing period of 3 sec. is invariably provided after the termination of the " Cross now " indication and before any further green indication.

In reply to Mr. McKinnon, there is no reason why pedestrian signals should not be used in Manchester just as much as in London. The signal systems in Manchester are of very early types, and apart from not catering for pedestrians do not afford the advantages of vehicle-actuation.

Capt. Nelson lays down the axioms that pedestrians are more difficult to control where traffic is intermittent as the pedestrians then cross where they like, and that vehicular traffic must to some extent be sacrificed if signal provision is made for pedestrians. It is necessary to tolerate the delays to vehicles while pedestrians are crossing, as subways cannot for economic reasons be provided universally and, also, those pedestrians in greatest need of protection are those least able to descend and mount the steps to and from the subways.

Asst.-Commissioner Brennan suggests that illuminated road studs of the type being tried out in Paris might solve the pedestrian problem. These, however, might cause pedestrians to look at the ground rather than at the traffic, while technical difficulties include ventilation of the lamps and provision for the heavy current which

would be necessary on account of the number of lamps being operated.

Detectors.

Mr. Preist's questions on this subject have been answered by Mr. Purkis and Mr. Riddle, and Mr. Riddle has also answered Mr. Matthews's question on sealing material.

Mr. Matthews suggests that the detector mat is a very unsatisfactory part of the equipment. I am not prepared to speak for all types, but as far as the electro-pneumatic type is concerned there is no more trouble-free part of the equipment. It will be seen from my replies under "Maintenance" that the detector-system fault-rate during January, 1938, was 0·04 per installation per month, representing one detector-system fault per installation in 25 months. In view of the heavy duty and the fact that at the average crossing there are four contact boxes and perhaps twice that number of mats, this cannot be considered to be unsatisfactory.

In further reply to Mr. Matthews, photo-electric cells have been tried and have been found less satisfactory than normal detectors. At first it might appear advantageous that there is no equipment in the road surface and that pedestrians are not required to press buttons; there are, however, the following disadvantages:—

(*a*) Risk of lamps burning out. All equipment must be duplicated.

(*b*) Continuous current consumption.

(*c*) No speed indication.

(*d*) It is necessary to erect a pillar in the centre of the carriage-way in order to detect approaching traffic only.

(*e*) Not unidirectional unless re-duplicated (i.e. quadruplicated) and associated with discriminating relays.

(*f*) Beams require very accurate focusing and can easily be thrown out of adjustment.

(*g*) Beams liable to obstruction (accidental and otherwise).

(*h*) Pedestrians compelled to register demands whether necessary or not, so obstructing traffic unnecessarily.

(*j*) Pedestrians transmit impulses when coming off the road as well as when about to cross.

Mr. Nettleship comments on the heavy duty and asks for details of the contacts and the method of protecting them from dirt, etc. The contact mechanism is contained in a V-shaped cast aluminium box with a glass cover. This is placed in the main contact box housing, which is of heavy cast-iron construction. A rubber gasket is interposed between the main housing and the cover, which is fastened by means of six bolts. The contact material is silver. Details of performance are given under "Maintenance."

In reply to Mr. Joseph, it should be explained that weight is no criterion for detector operation. The lightest vehicles should be able to operate detectors satisfactorily by their horizontal impact. The detectors described respond to thumb pressure and are tested in the street with the thumb, but heavy weights lowered slowly on to them would have no effect. The detectors are operated satisfactorily by all wheeled vehicles, including toy bicycles and wheelbarrows, but are operated by pedestrians only if pressure is applied to the air channel connected to the contacting bellows. As a consequence of the latter the system is less liable to malicious and accidental interference than if the whole surface were sensitive to vertical pressure.

Mr. Joseph and Mr. Hind require further particulars of operation of the contact box. The operation is that the bellows associated with the detector channel which is traversed first operates fully and mechanically prevents operation of the other bellows. Thus, if the contacting channel is traversed first an impulse is transmitted, while if the interlocking channel is traversed first there is no effect. Interpretation of the impulses as demands or extensions is effected entirely by the controller. There are only two wires from each contact box to the controller.

Use of detectors for "lane discipline."

Mr. Kingsbury suggests detectors to persuade drivers to use nearside lanes except when overtaking. While the manufacturers would doubtless be pleased to install such detectors, I feel that mobile police with loudspeakers educate drivers in matters of this kind more effectively and at a lower cost than would be possible with any permanent equipment. At the same time, however, the suggestion forms a good example of the unusual purposes to which detectors may be put.

Trams.

The information requested by Mr. Ridding is given on pages 128 and 130.

Timers and neon tubes.

Mr. Binns states that neon tubes are erratic, and he asks if other types of discharge tubes have been tried. Minor difficulties with neon tubes have occurred, but none sufficient to justify consideration of any alternative and more complex type of tube. The striking voltage of a neon tube varies with age and with the time since the tube was last used (i.e. since the gas was last ionized). The former is compensated periodically by means of the associated potentiometer; while the latter does not appear to be responsible for timing inaccuracies, owing to the smallness of the variations and on account of the shortness of the intervals between successive operations.

The reply to Mr. Jones's neon question is that the tubes comprise concentric cylindrical electrodes approximately 2 in. long, in glass envelopes approximately 4 in. long and $1\frac{1}{4}$ in. in diameter, with screw caps. The electrodes are kept correctly spaced by means of mica spacers. The general size of the tubes can be seen on Plate 2.

The striking potential depends largely on the pressure of the gas. Tubes with striking potentials as low as 80 volts have been produced experimentally, but were not sufficiently stable and also had a very low conductivity. The tubes used in the system described have a nominal striking potential of 170 volts.

It is very rarely indeed that it is necessary to replace neon tubes in working controllers.

In further reply to Mr. Jones, the resistances are of a carbon-sprayed type. The carbon is turned off on a lathe until the value is correct, thus giving great accuracy. The resistances are available from 10 000 Ω to 10 MΩ and have a rating of 2 watts.

Variations in supply voltages.

The questions asked by Mr. Hooper, Mr. Varcoe, and Mr. Allan, are very pertinent. Variations in supply voltages have in the past caused variations in timing which, in some cases, have been serious in nature; but all traffic controllers now manufactured incorporate voltage stabilizers, effectively overcoming the difficulty. The latest issue of B.S.S. No. 505 lays down that with variations in voltage of $\pm$ 6 % the timing variations must not exceed $\pm$ 10 %. The actual performance is very much better than this.

The voltage-regulating properties of neon tubes are well known, and in one form of stabilizer a neon tube is used to control the biasing potential applied to the grid of a thermionic rectifying valve.

Mr. Varcoe asks how any possible bad effects of voltage variations on the operations of the relays are overcome. The answer is that the margin of safety allowed when the relays are designed is so great that the effects of voltage variations may be neglected entirely. As stated in Mr. Bryan's contribution to the discussion the relays, which are normally fed from a 50-volt supply, operate satisfactorily even if the voltage drops as low as 22.

Impulse measurements.

Mr. Bryan makes some useful suggestions as to impulse measurement and recording, but the fact that all the methods mentioned in the paper have some imperfection is not such a disadvantage as might at first be imagined, as it is only necessary to measure vehicle impulses while a type of detector is being tested out prior to adoption.

Housing of control apparatus.

In reply to Mr. Nettleship, the controllers are housed in pressed-steel pillars with all doors well gasketed, but with breathing holes, protected by horsehair filters, under the roof canopy. Doors are provided as follows:—

(*a*) Control panel (timing switches).
(*b*) Controller mechanism (front).
(*c*) Controller mechanism (rear).
(*d*) A porthole door in the side of the pillar.

The last gives access to the main lamp switch and other switches which may have to be operated by a policeman, and is controlled by a Yale lock. All other doors are tightly bolted.

The pillar is fitted with a wooden board for power-supply equipment and miscellaneous apparatus (e.g. time switch). The controller rests on rubber buffers on a transverse angle-iron member and is secured by four bolts.

Wiring.

In reply to Mr. Cunliffe's questions, the materials and methods are entirely satisfactory for their purpose, and no added reliability would result from the use of larger conductors. The wire used for supply-main circuits (including signal lamps) is rubber-insulated, and the wire for the internal relay and timer circuits is enamelled to a thickness of 4 mils in addition to having the silk and braided cotton coverings which are customary for telephone equipment wiring. Fabric coverings are not permitted to touch any live metal, and the rubber and enamel insulation is continuous right up to each terminal.

Relays.

I am grateful to Mr. Bryan for his informative and authoritative contribution to the discussion which very much facilitates the work of replying to other speakers.

Mr. Barry questions the dependability of the telephone relay. A marked indication of the dependability is the fact that so many other speakers, including engineers responsible for the satisfactory performance of equipment largely comprising this type of relay, comment enthusiastically on its performance and capabilities. In addition to the use of the telephone relay for its primary function, it is found to be the most suitable device in almost every case where complex switching of light-current circuits is concerned, including public services (e.g. remote control of power equipment, and the broadcasting service) and where accuracy is required on account of large sums of money being at stake (totalizators), and even where matters of life and death are concerned (automatic S O S equipment on ships). Telephone relays are now manufactured in Great Britain at a rate exceeding 3 millions each year, and the experience gained in dealing with such large quantities has contributed very largely to their efficiency.

In reply to Mr. Nettleship's first question, the high-speed relay was developed primarily for stopping the drive of a uniselector capable of a speed of 400 contacts per sec., and the desired result was achieved by reducing the sizes of the inductive winding and of the mass of metal to be moved very much below the corresponding sizes on standard relays. The spring tensions are not less than the corresponding tensions on standard relays; thus the general standard of efficiency is maintained. Further information is given in the " Engineering Supplement " to *Siemens Magazine*, No. 110.

Mr. Nettleship and Mr. Gray ask regarding tungsten. This is used only for switching the signals (fed from the supply mains), and silver or platinum is used for all other contacts. The advantage of tungsten is that its melting point is as high as 3370° C. (i.e. higher than that of any other element except carbon, and comparing with 960° C. for silver), and as a consequence welding or " freezing " is almost impossible. This is a valuable feature in traffic-control work where it is important that it should not be possible, even under fault conditions, for conflicting green signals to be illuminated simultaneously. The disadvantage of tungsten is that a high-resistance oxide forms at arcing temperature. Provided, however, that steps are taken to prevent formation of this oxide, tungsten appears to be the most satisfactory material for the particular purpose. The precautions taken are the use of very high contact pressures (approximately 500 % greater than standard pressures), elimination of arcs by means of the special arc-quencher described on page 134, and a current limitation of 3 amperes (equivalent approximately to ten 60-watt lamps in parallel).

It has been found that slight modification of the standard telephone relay renders it more suitable for use as a contactor, and the following variations have been introduced:—

(*a*) The springs are actuated by insulating sleeves instead of brass pins.

(*b*) Steatite is used for the buffer blocks.

The above information partially answers Mr. Nettleship's last question on the subject of variations from standard Post Office practice. The only other variations are the inversion of the channel detail at the top of each springset, and additional layers of insulation between the core and the windings and between separate windings, on account of the high voltages used. These variations enable the relays to pass the 1 000-volt insulation test which is applied to all traffic-signal apparatus.

Right-turning traffic.

The answer to Mr. Cowley's question on the method of dealing with a junction with right-turning traffic on each road is that a 4-phase 4-part-cycle controller would be used. The four roads would each have separate right-of-way periods.

I agree with Mr. Cunliffe's suggestion that the late-start facility used in conjunction with the early cut-off facility would satisfactorily prevent the traffic cut off first from being stopped altogether. There are now several examples of controllers operating on this basis.

Mr. Brown appears perturbed regarding the possibility of accidents when traffic is permitted to turn right, but in actual practice serious difficulties do not appear to arise and, in any case, the position with signals is certainly no worse than without them. Right-turning traffic must always give way to straight-through traffic in the opposite direction.

In reply to Mr. Bredin, the drivers having the extended period do not have to know that the signals have stopped the opposite traffic. The fact that the traffic has stopped is sufficient for them to be able to complete their right turn.

Replying further to Mr. Bredin, the right-turning traffic at such junctions as at both ends of Dawson Street (Dublin) would not be segregated from the straight-through traffic and each road would be signalled as a whole. The traffic-marshalling would remain substantially as at present.

Clearing periods.

Mr. Matthews recommended standardization of the amber period, and it will doubtless be some satisfaction to him that the period was standardized only a few days later. In reply to Mr. Hooper, amber periods have in the past varied between the limits of 1 and 12 sec., but the new standard value is 3 sec. Where long clearing periods are necessary the consequent amber and overlapping red facilities (see page 139) are employed.

Mr. Margary asks if any attempt has been made to do away with the amber indication. An experiment of substitution of an overlapping red period for the usual amber period was conducted in Oxford Street, as described in the "Report of the Departmental Committee on Traffic Signs,"* and resulted in the conclusion that amber indications are necessary.

Capt. Nelson's contention that overlapping red periods are preferable to "Cross now" periods is probably correct once the pedestrians have commenced to cross, but the "Cross now" signal is definitely useful in informing pedestrians when they may safely commence crossing.

* See Bibliography, (13).

Miscellaneous controller facilities.

Variable Maximum Green Facility.—Mr. Riddle foreshadows a means of varying the duration of the maximum green period in order better to suit the traffic. The delays to waiting traffic by widely spaced vehicles in the running phase, which may continually arrive (in the two opposite directions) just in time to reset the speed timer, can be very much reduced by use of such an arrangement.

Variable Minimum Green Facility.—Mr. Cunliffe, in suggesting variation of the minimum green period according to the number of vehicles waiting, has hit on a problem to which no ready solution has yet been found. If the minimum green period is to be infinitely variable or variable in a number of steps over a wide range, then counting devices and possibly speed-indicating devices are necessary for each road. The necessity of counting the traffic in the two opposite roads of a phase arises from the possibility of the two traffic streams being in one case balanced and in another case completely unbalanced and together having the same total traffic in each case. Such devices could be provided, but would make the controllers uneconomic. A simple counting scheme to convert from a short minimum green period to a long one and vice versa has been developed, but not yet adopted.

Narrow-Bridge Problem.—This problem described by Mr. Onley could satisfactorily be solved by use of a controller which provided separate right-of-way periods for the pedestrians, preferably introduced by operation of push-buttons. Apart from the advantage to pedestrians, the controller would prevent vehicles entering the narrow portion of the bridge while traffic was proceeding in the opposite direction.

Steep-Hill Problem.—The most satisfactory method of dealing with the problem described by Mr. Woollaston would be by using two controllers operating on the flexible progressive system. One of the controllers would be located at the bottom of the incline (not necessarily at a junction) and would hold back the traffic until it could be assured of right-of-way past the signals on the hill. This could be done by means of the vehicle-actuated progressive system described in the paper.

Emergency Control.—The answer to Mr. Breton's question is that in the event of a fire or other cause of traffic obstruction the signals at selected junctions could, if necessary, be switched off, but if they were operated on the vehicle-actuated principle they would to a very large extent adapt themselves to the changed conditions.

Flexible progressive systems.

In reply to Mr. Taylor, it is agreed that the disadvantages described in connection with the typical fixed-time progressive system do apply only to the particular system described, and there may be other fixed-time progressive systems without such disadvantages. For example, the vehicle-actuated progressive system described would not suffer from such disadvantages if it were used for fixed-time control. The general disadvantages of fixed-time progressive systems are those stated at the head of the second column on page 141.

I thank Mr. Bellamy for his authoritative contribution on practical difficulties of time and distance diagrams. Even when allowance is made for such difficulties, however, the disadvantages of fixed-time progressive systems

can readily be seen from Fig. 24. The majority of the runs included a number of stops, as the predetermined speed was too high or too low for the amount of traffic at the particular time. The arbitrary changing-over of the fixed-time signals was undoubtedly responsible for many of the stops, including all four in run No. 9 (5.10 a.m.). These defects could be avoided by use of a traffic integrator and by vehicle actuation at the local controllers.

Col. Carty asks if the police can alter the systems in Chicago according to the time of day and density of the traffic, and he suggests that such adjustment is an advantage. Such adjustment is undoubtedly an advantage and is frequently a necessity when the controllers are not vehicle-actuated. In the vehicle-actuated progressive system described, however, it is quite unnecessary, as both the cycle times and the proportions of the cycle allocated to the various phases are automatically determined far more accurately and frequently than could be done by any human control.

The reply to Mr. Murray is that a number of short interlinked systems in streets equivalent to Deansgate already exist (several examples can be seen in Fig. 25), and, no doubt, the manufacturers would be only too pleased to have the opportunity of dealing with the problem of Deansgate.

Asst.-Commissioner Brennan asks what is the minimum spacing between junctions before the flexible progressive system could be applied. The answer is that the closer the junctions the more necessary is efficient interlinking. Several examples of flexible progressive control applied to close groups of intersections can be seen in Fig. 25 and in the test-run records in Fig. 29. Without progressive control in such cases it would be impossible to prevent blocking back from one junction across another.

Mr. Purkis has answered Mr. Preist's question on the traffic-density—cycle-time—speed relationship. The speed set by the signals is certainly inversely proportional to the cycle time, but neither speed nor cycle time varies inversely or directly as the traffic density. By means of the jumper field on the integrator all the traffic densities can be associated with any of the available cycle times. The densities are associated with the cycle times which produce the most suitable speeds in the varying circumstances. In certain cases it is, as Mr. Preist suggests, not only desirable to vary the cycle time as the traffic varies but also to change the whole planning of the time and distance diagram, and this is done in the system recently brought into use in High Street, Exeter, and will shortly be done also in another system to be installed in Kensington High Street.

Mr. Preist has cited two cases of progressive systems incorporating 4-phase local controllers. Proposals for other similar local controllers have recently been made, and it appears that use of such complex controllers is spreading. Four-phase controllers involve four or five cycle parts, and on the assumption that each part has an average duration of 25 sec. a cycle time of 100 sec. is needed. A 2-phase, 2-part-cycle, controller with similar part durations needs a cycle time of only 50 sec. The long cycle time of the most complex local controller is necessarily a limiting factor of the whole system, and in a mixed system this can be a serious disadvantage. It is perhaps the difficulty of mixing controllers of different degrees of complexity which is responsible for the present tendency to provide a number of small systems, each with only two or three local controllers, in place of larger systems.

I thank Mr. Hounsfield for his suggestions on the subject of describing the "Prevent" and "Privilege" periods, and agree that the method suggested would be a great improvement for indicating the purposes of these periods.

In connection with Mr. Wray's remarks it is a fact that I attach very great importance to the efficiency of interlinking, but the proportion of the paper devoted to progressive systems is perhaps not quite so unbalanced as might at first be supposed.

The biasing effect to which Mr. Wray refers is obtained by means of quick-discharge circuits for the speed-timer and maximum-timer condensers formed by contacts of the preference-indicating relay, the lamp-control relay, and the demand relay. The contacts are arranged so that a demand in the road having preference but not having right-of-way is able to force an immediate change-over if necessary.

In further reply to Mr. Wray it is agreed that vehicles freed early at one junction by the vehicle-actuation feature may arrive at subsequent junctions out of plan and be stopped, but, on the other hand, the drivers may wish only to turn left or right or they may drive sufficiently fast to join the tail of the preceding traffic band. In any of these cases early liberation is an advantage. It should be borne in mind that in fixed-time systems vehicles turning left or right are almost certain to be out of phase for the new direction. In fixed-time systems it is also impossible for drivers to transfer to the next traffic band ahead, even when conditions are suitable for them to do so. The fact that vehicle-actuated signals may change in favour of a certain route early, or may remain in favour of a route for a period of several cycles also enables the system to give better treatment to vehicles proceeding at speeds other than that imposed by the progressive control.

The comparative test runs quoted by Mr. Adams are very illuminating and useful but call for further comments on my part. As pointed out by Mr. Adams, the conditions for the two sets of test runs may be different. In addition to variations due to the time of year, the traffic density generally has increased. and at Marylebone Circus now exceeds 4 000 vehicles per hour during the evening rush hour (compared with the figure of 3 600 v.p.h. quoted on page 153). The probable explanation of the low average speed in the case of Baker Street, southbound, is that the number of test runs was not sufficient to be representative. Further, the speed of run No. 8 (taxicab) was unnecessarily low—much lower than the general traffic speed—and as a consequence the vehicle did not keep in phase with the signals and was stopped several times. (I have, in the past, avoided instructing my drivers as to their speed.) Other possible causes of low speed in Baker Street are: (1) that it is necessary to pass from one progressive system to another; (2) that the controller at the junction of Portman Square and Wigmore Street is 3-part-cycle whereas all the remainder are 2-part-cycle; and (3) that Group III is not controlled by an integrator. Table B demonstrates

perhaps better than Table A the improvement gained under conditions of signalling, and forms ample justification for the system adopted.

Mr. Chance has raised the question of horse-drawn traffic, and has quoted the proposed progressive system for Butt Bridge. As Mr. Stewart points out, horse-drawn traffic at 2·5 m.p.h. forms 40 % of the traffic across this bridge. (Butt Bridge is the first bridge across the Liffey, and as a consequence carries very heavy dock traffic.) I suggest that this could be met by isolated controllers with special provision for slow-moving vehicles when the horse traffic is present, and by means of a progressive system at other times. Conversion could be effected by a traffic integrator.

The synchronous system.

Mr. Palmer states that actual journeys never follow time and distance diagrams, and he advocates the synchronous system in place of the flexible progressive system. Reference to Figs. 29A–29F shows that, on the contrary, the majority of journeys through progressive systems follow the time and distance diagram remarkably well, particularly when a traffic integrator is used.

The synchronous system was the forerunner of the "limited progressive" system, which, in turn, led up to the "flexible progressive" system. In the synchronous system the whole of the north and south traffic in the town was allowed to flow for a certain period (usually about 2 minutes) while the whole of the east and west traffic was stopped, after which the condition was reversed.

It is believed that the system has been abandoned wherever it has been tried. Its disadvantages are as follows:—

(1) The system is confined to 2-phase controllers. It is not possible to introduce special periods for turning traffic or pedestrians, or to take into account unusually shaped junctions (i.e. the multiphase controller, early cut-off facility, late-start facility and overlapping red facility, are all barred). The ratio of north-south to east-west right-of-way time must be the same at all junctions whatever the traffic volumes.

(2) There is no means of preventing "blocking back" from one intersection across another. This results in obstruction to the traffic having right-of-way and is particularly serious when junctions are close together.

(3) The enforced long stops (which are in many cases unnecessary, particularly at night time) lower the efficiency and prestige of the system.

(4) Where tramways or trolley-buses are concerned, an abnormal load is thrown on the power station whenever the signals change, as the whole of the vehicles in either the north-south or the east-west direction start simultaneously.

(5) Drivers, knowing the duration for which the signals will remain in their favour, are encouraged to drive at dangerously high speeds.

Colour blindness.

Several speakers ask questions and make suggestions for signal alterations on account of difficulties experienced by colour-blind persons. I would say that the problem has been given careful consideration and it has been found that serious difficulties do not arise in practice. Details are given in paragraph 115 in the "Report of the Departmental Committee on Traffic Signs."* Further information is given in an article by Dr. W. M. Hampton entitled "Developments in Glassware used for Railway Signalling" and published in *World Power*.†

To Mr. Cooper I would say that the problems associated with the use of semaphore indications preclude use of such indications. It is impossible to guarantee that a number of separate mechanical devices located on all the signal posts will always operate faultlessly and remain in phase with one another.

Mr. McKinnon raised the matter of colour-blind pedestrians. Traffic signals should not trouble colour-blind pedestrians, as pedestrians are instructed in the Highway Code not to rely solely on signals unless "Cross now" indications are used, and "Cross now" indications are in black and white only.

Damage to equipment.

The reply to Mr. Sheppard's question on protection of cables is that, in the system described, armoured cable is used for all purposes, including signals, detectors, and progressive interlinking except in a few cases where supply of the cable is not in the hands of the main contractor (e.g. the Post Office cables in St. Marylebone). The armoured cables are carried under roads in ducts, and under footpaths are generally covered by protective bricks impressed with the words "Electric Cable." The cables in St. Marylebone are in ducts in the standard Post Office manner.

Mr. Cooper's suggestion to obviate failure of all the signals when one signal post is knocked over could be effected by providing a separate fuse, in the controller pillar, for every cable core.

Maintenance.

The following notes refer particularly to the system described in the paper, but information regarding the maintenance of another system can be found on page 20 in the issue of the *Commercial Motor* dated the 14th February, 1936.

The maintenance organization falls into the following groups:—

(*a*) Signals: regular cleaning of lenses and replacement of lamps every 1 000 burning hours.

(*b*) Routine inspections, at 3-monthly intervals.

(*c*) Emergency "beck and call" service.

The signals proper are maintained sometimes by the local authority and sometimes by the manufacturer, but the remainder of the equipment is maintained in almost every case by the manufacturer.

The manufacturer's organization comprises the stationing of groups of maintenance engineers in London and nine provincial centres. The maintenance of private automatic telephone exchanges is handled by the same staff, so making it economically possible to locate engineers in areas where the signals or the telephones alone would not justify this course, and thereby affording a considerably quicker response to service calls than would otherwise be possible.

The maintenance engineers engaged on routine inspec-

* See Bibliography (13). † *World Power*, 1932, vol. 18, p. 227.

tions are provided with questionnaire sheets setting out the principal items to be checked and, if necessary, rectified or reported for attention. The principal items are:—

Controller.—Condition of controller—dampness—dust; power unit output voltages; dynamotor (when used)—greasing—brushes; timings; fuses and neon-tubes tight; relay sets; spare lamps in controller; general functioning.

Detectors.—Condition of contact boxes—contacts—examine for presence of water; condition of mat treads and road reinstatement; tram detectors.

Signals.—Focusing; cleanliness; damage.

Special attention is devoted to the relays. These are subjected to a routine which includes: Tighten buffer blocks, spring sets, residual screws and armature screws where necessary; examine for presence of dirt or stickiness; try tensions of neon-tube relays and tungsten contactors; visually inspect all relays.

The maintenance of detectors entails quarterly adjustment, and replacement every two or three years, of the contacts in the contact boxes. It is interesting to note that a traffic flow of 500 vehicles per hour for 20 hours a day operates the contacts over 7 million times a year.

By means of the routine inspection the equipment is kept in as good condition as possible and faults are anticipated and prevented rather than allowed to develop.

Mr. Morris asks which of the three main items—signals, controllers, and detectors—gives the most trouble. The controllers, forming the most complex part of the system, are responsible for most of the faults reported, while the detector systems give least trouble.

The following figures relate to January, 1938:—

	Total	No. per installation per month
Systems maintained	346	—
Calls on maintenance service ..	204	0·59
Total faults found	127	0·37
Controller faults	72	0·20
Detector-system faults	15	0·04
Cable faults	0	0·00
Signal faults (including lamps) ..	20	0·06
Mechanical damage (collisions, etc.)	8	0·02

I agree with Mr. Anson's views on the restriction of complexity, in the interests of efficient operation and easy maintenance. Operating authorities have during the last few years realized more and more the capabilities of vehicle-actuated signals and their flexibility of design, and have been specifying unusual requirements for junctions where a few years ago a simple scheme might have been applied. The manufacturers can supply controllers for such unusual schemes, but prices must necessarily be higher than for standard controllers and delivery periods must be a matter of several (sometimes many) months instead of a week or two as in the case of standard controllers. Local authorities find it difficult to appreciate the necessity for design and manufacturing periods in such cases, and become impatient at the apparent lack of progress. Special controllers present a serious problem to the maintenance organization, inasmuch as the staff cannot get to know the details of either the control schemes or the circuit details nearly as well as in standard controllers, and much more reference to drawings and descriptive matter is involved. The tracing of faults is more difficult than in standard controllers or in telephone exchanges, particularly under the special conditions applicable to work in the street—weather, traffic, curious spectators, illumination, dirt, etc. This dissertation should not be taken as indicating that unusual and complex controllers are not a practicable proposition—on the contrary, all the 4-phase and 5-phase controllers known to me are operating satisfactorily. At the same time, however, signal breakdowns can so rapidly result in congestion that, in my opinion, all possible steps should be taken to minimize the risk of failure and to reduce the out-of-service time when faults do occur. One means of improving the conditions would be that suggested by Mr. Thompson, namely, to locate the equipment inside telephone exchanges. On account of the amount of cabling that would be necessary this would have limitations, but there is no reason why telephone exchanges and other suitable buildings (municipal offices, electricity substations, etc.) in the vicinities of controlled junctions should not be used. (It should be explained that the system installed in the telephone exchanges in Amsterdam, with three telephone pairs per controller, is suitable only for straightforward 2-phase operation, without overlapping red or other special facilities. Considerably more cabling would be necessary if more complex control schemes were required.)

Mr. Matthews inquires whether there is any means of automatically replacing defective parts by duplicates. Master controllers are frequently constructed in duplicate with automatic change-over in case of failure, with visual alarm lamps. In St. Marylebone the alarm circuits are extended through the Post Office telephone system to a police station and to the Council depot. Local controllers are arranged to convert automatically to isolated operation in the event of breakdown of the progressive control, and are also fitted with alarm lamps. Apart from progressive systems, however, such precautions do not appear to be justifiable or necessary.

Mr. Morris also asks what would be the effect on a long system if one controller gives trouble. The effect would depend on the particular fault. It can be visualized that the signals might stop working with right-of-way on the side road, when the effect on the main road traffic would be serious; but, on the other hand, the signals might stop with right-of-way on the main road. Regular routine inspections, however, minimize the risk of such occurrences.

Power failure.

In reply to Mr. Kerr, cases where the authorities consider continuity of operation sufficiently important to warrant the provision of alternative supplies are very rare, no doubt on account of cost and installation difficulties, together with the fact that power failures are continually becoming less frequent. Even if the control equipment for a number of junctions were installed centrally the cost of batteries or prime movers with generators would probably be prohibitive.

The matter of ensuring safety in the event of failure of

the power is raised by Mr. Allan. There is no easy and cheap means of continuing automatic control in such a circumstance, and the drivers would naturally attempt to cross the junction at the earliest opportunity. They would, nevertheless, be under their normal obligation to drive with safety and with due regard to other traffic. If the traffic were at all dense, congestion would result until a policeman or civil guard took control, but power supplies now fail so rarely that such temporary congestion is tolerated. Mr. Allan also asks what could be done to avoid dangerous situations when the power supply was restored. If the drivers regard the green indication which may suddenly appear as meaning " Proceed with caution " there should be no necessity to take further steps, but it may be added that, in the system demonstrated, an amber period precedes any green indication when current is connected to a dead controller. (This is an accidental feature consequent upon the use of the discharge form of neon-tube timer.)

Post Office influence.

One cannot but agree with Mr. Anson's remarks on the influence of the Post Office and telecommunication practice generally on traffic-control problems. It would be possible to use apparatus other than that designed for telecommunications, but such other apparatus would be clumsy and large and would lack the adaptability of the telecommunication apparatus.

Further, experience gained by use of very large numbers of each component in telephone exchanges during the course of years has resulted in elimination of defects and standardization on proved apparatus. There is, therefore, every reason for confidence when such apparatus is used for new purposes such as traffic control.

Mr. Anson also touches on the subject of circuit diagrams. The complex requirements of automatic telephone apparatus necessitated a new method of circuit representation—" detached contacts "—and this has naturally been used in all cases where similar apparatus has been adopted. The symbols and principles form the subject of B.S.S. No. 530.

Mr. Peck mentions that the Post Office provides the cables for interlinking. This is certainly so in some of the largest interlinked systems, but is by no means general. Such cables are designed primarily for telecommunication purposes, and to prevent interference with their normal services the Post Office are obliged to lay down drastic restrictions (see B.S.S. No. 505). As a consequence manufacturers generally prefer to provide their own cables. The cables for the progressive systems in St. Marylebone were provided by the Post Office, and reference to the map on page 144 indicates the magnitude of the undertaking. In addition to the signalled routes shown, telephone pairs were provided from each master controller to a local police station and to the Council's depot, for alarm purposes, and *en route* pass through the main distributing frames of various telephone exchanges.

Comments on the remaining points raised by Mr. Anson and Mr. Peck appear under " Maintenance."

The Post Office have also been of great assistance to the manufacturers in the matter of radio-interference suppression and have recently conducted extensive tests on the shorter wave-bands. The results of such tests are of material use to the manufacturers not only in this country but also overseas.

Hours of operation.

Mr. Peck suggests that the practice of switching off signals at night time is undesirable and that when signals are so switched off amber globes should always be illuminated. I agree. With fixed-time signals switching-out at night time is desirable owing to the risk of disobedience when drivers are stopped unnecessarily, but the increased safety and quietness which result from the use of vehicle-actuated signals justify operation of such signals throughout the day and night.

Miscellaneous questions.

Mr. Hunt's experience with bullocks at Worcester emphasizes the necessity to regard the green signal as inferring no more than " Proceed with caution." The signals would not necessarily change over immediately in favour of the bullocks, assuming that one of their number did operate the detector, as it is possible that Mr. Hunt's car or some other traffic had registered extensions.

Mr. Margary asks for a flickering light to call attention to the signals. There should be no necessity for this with modern efficient optical systems: in fact, the signal intensity should be many times that of any such flickering light.

The solution to Mr. Rawll's problem of parked vehicles preventing other traffic from crossing detectors is to install detectors of adequate length. It is, nevertheless, bad practice for a vehicle to be parked across a detector or, in fact, near any road junction.

Mr. Parkinson suggests that the Ministry of Transport veto proposed traffic signal schemes on account of there being either too little or too much traffic. I am not in possession of authoritative information regarding the conditions under which the Ministry permit signals to be installed, but many of the busiest junctions are handled by signals. At the other extreme it is probable that signals are not sanctioned purely on economic grounds. There are, of course, many lightly-loaded junctions which could be rendered safer by the use of signals.

Dr. Robinson has referred to the problem of controlling a number of awkward-shaped junctions in the neighbourhood of Manchester. The junctions in question would, in most cases, necessitate the use of multiphase controllers but would otherwise present no great difficulty.

The reply to Mr. Palfrey's question on the subject of visual alarms is that such devices, together with automatic routine-testing equipment, could be provided if highway authorities considered the cost justified. In the system described (using pneumatic mats) short-circuited detectors are almost unknown.

Lt.-Col. O'Brien states that a difficulty when providing signals is the lack of pre-knowledge of what traffic is going to do, and he quotes the example of a block of traffic moving from Oxford Circus to Piccadilly Circus. The use of vehicle actuation, however, renders such pre-knowledge unnecessary.

In reply to Lt.-Col. O'Brien's second question, the use of signals in gyratory layouts can materially increase the safety, and there are numerous cases where the use of signals is almost a necessity.

THE CALIBRATION OF SPHERE-GAPS WITH IMPULSE VOLTAGES

By R. DAVIS, M.Sc., Associate Member, and G. W. BOWDLER, M.Sc.

(*Paper first received* 1st *June, and in final form* 12*th October*, 1937; *read before the* METER AND INSTRUMENT SECTION 7*th January*, 1938.)

SUMMARY

The technique of measuring impulse voltages with the aid of the high-voltage cathode-ray oscillograph and the resistor voltage-divider is discussed, and applied to the determination of the minimum impulse flashover characteristics of gaps between spheres ranging in diameters from 125 mm. to 1 000 mm. Flashover measurements on sphere-gaps have also been made at power frequencies and compared with the corresponding figures for impulse voltages.

The results of some previous workers are considered, and compared with those obtained by the authors.

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(1) INTRODUCTION

For the measurement of voltage the sparkover in air between suitable electrodes has long been used as a sub-standard. Rules for the measurement of voltages at power frequencies with the aid of sphere-gaps are given in British Standard Specification No. 358—1929. The calibration curves given therein are at present being revised and extended by a Committee of the International Electrotechnical Commission, their recommendations being restricted to power-frequency voltages. Meanwhile the flashover characteristics of sphere-gaps with impulse voltages have been investigated by workers both in America and in Europe, with a view to extending the use of the sphere-gap as a standard of reference.

The present work has been undertaken to obtain an independent set of calibrations for sphere-gaps to aid in the formulation of impulse flashover figures which might be generally acceptable; and to examine the measuring technique.

Most previous workers* have concluded that the flashover values for power frequency and the corresponding negative impulse voltages are the same. The authors have made some tests with power-frequency voltages to examine this conclusion. They find that the power-frequency flashover value is always less than the corresponding negative impulse figure, the difference being approximately 5 % at a spacing equal to the radius of the spheres. It would appear that the correlation between power-frequency and impulse flashover would merit further investigation.

* W. Holzer has published results (*Elektrotechnik und Maschinenbau*, 1937, vol. 55, p. 134) showing the power-frequency calibration curve for spheres as lying between the corresponding positive- and negative-impulse curves. The authors are informed, however, by Dr. W. Weicker, that Holzer has since indicated to him that his figures are in error.

(2) SUMMARY OF RECENT WORK

Recent work has been carried out by J. R. Meador,* P. L. Bellaschi and P. H. McAuley,† and W. Dattan.‡ In Dattan's measurements the spheres were mounted horizontally, and in the case of the others, vertically. By means of a shielded neon lamp placed across a resistor connected between the lower sphere and earth, Meador determined the relation between the percentage number of flashovers in the positive half-cycle and the gap separation, with power-frequency voltage. Beyond a certain spacing (30 cm. in the case of 100-cm. spheres) he found that flashover occurred predominantly in the negative half-cycle. For spacings below this value he concluded that there was no polarity effect, and that consequently the calibrations for power frequency and for positive and negative impulse voltages were identical. The calibration over this range could consequently be used to determine the flashover characteristics of smaller spheres both with power-frequency and with impulse voltage. This procedure was adopted by Meador; spheres of 200-cm. diameter were calibrated on alternating current up to a value of 800 kV (peak) by means of a testing transformer fitted with a voltmeter coil; the coil voltage was rectified to obtain the peak value. The wave-shape of the voltage given by the testing transformer and the coil were compared by cathode-ray oscillograms, and tests, it is stated, were made to check the ratio of transformer voltage to coil voltage under all conditions of excitation of the transformer. The calibrations of the various spheres were made to depend on the power-frequency calibration up to 800 kV (peak) of the 200-cm. spheres.

Both sets of calibrations by the other investigators were carried out by means of the cathode-ray oscillograph used in conjunction with a resistor voltage-divider. For the high-voltage arm of the divider Bellaschi and McAuley used a wire resistance wound non-inductively, and immersed in oil, the value being from 5 to 10 ohms per kV of maximum operating

* *Electrical Engineering*, 1934, vol. 53, p. 942.
† *Electric Journal*, 1934, vol. 31, p. 228.
‡ *Elektrotechnische Zeitschrift*, 1936, vol 57, pp. 377, 412.

voltage, while Dattan used a liquid resistance of approximately 70 000 ohms. The latter claimed that the accuracy of the recording was within 0·5 %, while the former by comparing records obtained with the resistor and a capacitor divider concluded that no distortion was introduced by the resistor divider.

Table 1

Diameter of spheres (mm.)	Minimum value of s/d, showing polarity effect			
	Meador	Bellaschi and McAuley	Dattan	Present authors
1 000	0·30	0·25		0·30
750	0·22	0·29	0·12	0·27
500	0·31	0·34	0·16	0·35
250	0·35	0·32	0·22	0·29
150			0·29	
125	0·35	0·24		0·20
100			0·35	
62·5	0·83	0·48		
50			0·49	

The results obtained by these workers indicated that beyond a certain spacing polarity effects occurred, the positive being higher than the negative impulse value. In Table 1 the minimum ratio s/d (s = spacing, d = diameter of spheres) showing polarity effects is given for spheres of various sizes.

Only in the case of Dattan's results does the value of s/d, corresponding to the first appearance of the polarity effect, bear a smooth relation to the diameter of the spheres. The magnitude of the polarity effect obtained is indicated in Table 2, where the percentage difference between positive and negative impulse flashover voltage at a spacing equal to the radius is shown for spheres of various diameters.

Table 2

Diameter of spheres (mm.)	Percentage difference between positive and negative impulse flashover voltage (s/d = 0·5)			
	Meador	Bellaschi and McAuley	Dattan	Present authors
1 000	3·5	4·0		3·0
750	5·5	4·0	14·0	2·5
500	5·5	5·0	15·5	2·5
250	7·5	5·5	14·0	3·5
150			11·5	
125	8·5	5·5		4·0
100			7·5	
62·5	0	1·5		
50			5·5	

Meador, and also Bellaschi and McAuley, found that the polarity effect at a spacing equal to the radius is for the larger spheres approximately the same, and only of the order of 5 %, whereas the effect found by Dattan was more than twice this value. As Dattan was the only one to use spheres in the horizontal position, the difference in the effects obtained may be due to set-up.

(3) IMPULSE-VOLTAGE TESTS

(a) Method of Measurement

The voltage delivered by the impulse generator was adjusted until sparkover occurred in approximately 90 % of the applications. The voltage wave was then recorded on the high-voltage cathode-ray oscillograph: in some measurements the gap was opened so that a record without flashover was obtained. Some check measurements were made by comparing spheres of one size with those of a larger size which had already been calibrated.

The measuring circuit is illustrated in Fig. 1. In conjunction with the oscillograph a resistor voltage-divider was used. This consisted of a liquid resistance R_1 contained in a bakelized-paper tube, non-inductively-wound wire resistors R_2 and Z, and a delay cable to

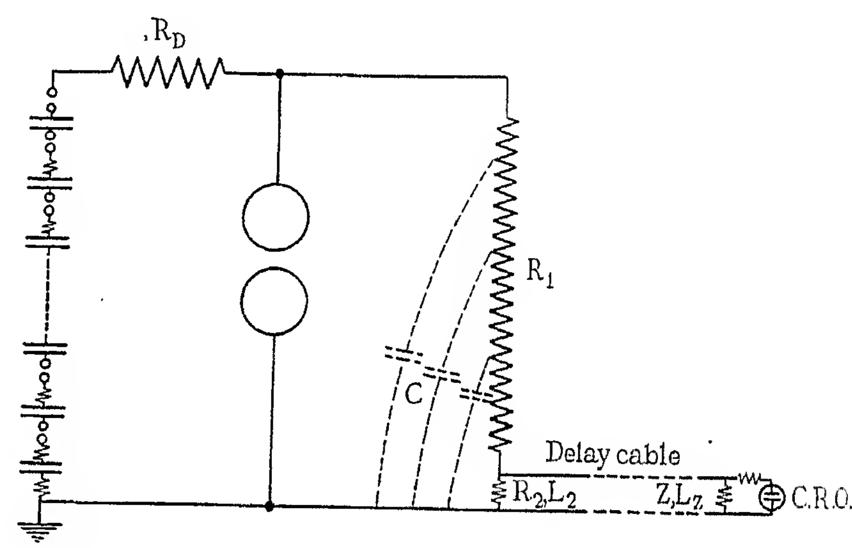

Fig. 1

provide a suitable interval between the operation of the generator and the arrival of the surge at the oscillograph deflecting plates. The delay cable was approximately 300 m. long, and consisted of an inner copper tube of 6·4 mm. diameter connected to R_1, and an outer brass tube, concentric with it, of 49·2 mm. diameter. The inner tube was located in the outer tube by ebonite discs $\frac{1}{4}$ in. thick, spaced at intervals of a metre. The surge impedance of the cable was 121·5 ohms, and the resistor Z terminating the cable across which the oscillograph plates were connected through a damping resistance of 1 000 ohms was made equal to this value to avoid voltage reflections from this end. Inter-stage damping resistors totalling 300 ohms were used in the impulse generator as well as the external damping resistance R_D, and the high-voltage connections were made with 50-mm. diameter brass tubing. Tests were made on gaps between spheres ranging in diameter from 1 000 mm. to 125 mm. All the spheres were mounted vertically. The 1 000-mm. and 750-mm. spheres were arranged with the gap approximately midway between floor and roof of a laboratory about 14 m. high; the nearest earthed object was approximately 5 m. from the gap.

The remaining sizes of spheres were mounted on self-contained transportable frameworks. In each case the lower (earthed) sphere was 3 diameters or more above ground. In no case was any attempt made to activate the spheres by ultra-violet light, radio-active salts, etc. The 125-mm., 250-mm., and 1 000-mm. spheres were made of aluminium, the 500-mm. and 750-mm. spheres of copper.

(b) Accuracy of Measurements

If V be the amplitude of voltage applied to the sphere-gap, and v the amplitude recorded, then

$$\frac{V}{v} = \frac{1 + R_1(R_2 + Z)}{R_2 Z} \quad . \quad . \quad . \quad . \quad (1)$$

The right-hand side of equation (1) is constant, and therefore v should be a true copy of V. The resistors used, however, possess self-inductance, self-capacitance, and capacitance to neighbouring objects. The resistors R_2 and Z consisted of approximately 50 cm. of constantan wire wound zigzag on one side of a mica card, and clamped between keramot plates carrying connections to the resistance wire. The value of R_2 ranged from about 7 ohms to 100 ohms, while Z was constant and equal to 121·5 ohms. The measured value of the residual inductance was 0·35 microhenry in every case: the time-constants range, therefore, from 3×10^{-9} to 5×10^{-8} sec. These times are short compared with the times involved in most impulse phenomena. If unit rectangular current enters the low-voltage arm of the divider the recorded voltage v is of the form:—

$$v = k(1 + k_1 e^{-\frac{t}{t_1}} + k_2 e^{-\frac{t}{t_2}}) \quad . \quad . \quad . \quad (2)$$

where $t_1 = L_2/(Z + R_2)$, $t_2 = L_z/(2Z)$, L_2 and L_z being the respective residual inductances of R_2 and of the terminal resistor Z with the oscillograph plates connected in parallel. The time-constants t_1 and t_2 are of the order 10^{-9} sec., so that the second and third terms on the right-hand side of equation (2) can be neglected.

The resistor R_1 consisted of a salt solution filling a bakelized-paper tube 400 cm. long and 5 cm. diameter. The capacitance to earth was 85 $\mu\mu$F, and if this value be multiplied by a typical value of R_1—say 10^4 ohms—the resulting product is a time-constant comparable in magnitude with the time occupied by the front of an impulse wave. The effect of this capacitance is to lengthen the front and to reduce the amplitude of the recorded wave.

It is shown in the Appendix that, if unit rectangular voltage is applied to the divider, the current entering the low-voltage arm is approximately i, where

$$i = \frac{1}{R_1}\left[1 + 2\sum_{m=1}^{m=\infty}(-1)^m e^{-\frac{m^2\pi^2}{CR_1}t}\right] = F_1(t) \quad . \quad (3)$$

and C is the capacitance of R_1 to earth, assumed uniformly distributed. Thus a voltage wave of vertical front is recorded as one with a front of finite time. For any voltage V of wave-shape given by $F_2(t)$, the current $i(t)$ entering the low-voltage arm is given by

$$i(t) = F_1(0)F_2(t) + \int_0^t F_1'(\lambda)F_2(t-\lambda)d\lambda$$
$$= \int_0^t F_1'(\lambda)F_2(t-\lambda)d\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The integral on the right-hand side of (4) represents the wave-shape recorded when the actual wave is $F_2(t)$. For a typical wave-shape in which $F_2(t) = V(e^{-\alpha t} - e^{-\beta t})$, equation (4) becomes

$$i(t) = \frac{2\pi^2 V}{CR_1^2}\left[\sum_{m=1}^{m=\infty}\frac{(-1)^{m+1}m^2 e^{-\frac{m^2\pi^2}{CR_1}t}(\beta-\alpha)}{\left(\alpha - \frac{m^2\pi^2}{CR_1}\right)\left(\beta - \frac{m^2\pi^2}{CR_1}\right)} - \sum_{m=1}^{m=\infty}(-1)^{m+1}\left(\frac{e^{-\alpha t}}{\alpha - \frac{m^2\pi^2}{CR_1}} - \frac{e^{-\beta t}}{\beta - \frac{m^2\pi^2}{CR_1}}\right)\right] \quad (5)$$

The numerical evaluation of equation (5) is laborious, and a graphical method has been adopted. For any given value of t a product curve $F_1'(\lambda)F_2(t-\lambda)$ can readily be constructed, and its area between the limits 0 and t determined. By repeating the process for different values of t the complete wave-shape can be evaluated. This procedure has been carried out for a number of typical wave-shapes, and for different values of the product CR_1. The resulting curves, reproduced in Fig. 2, show that the effect of increasing the product CR_1 is to lengthen the front and the back and to reduce the maximum amplitude of the recorded wave. The time occupied by the wave-front (defined as 1·25 multiplied by the time occupied in increasing from 0·1 to 0·9 of the maximum value) and the error in the recorded maximum value have been obtained from these curves, and are plotted beneath the corresponding wave-shape curves as functions of CR_1.

This distortion was investigated experimentally. The impulse generator was arranged to deliver an aperiodic wave with a front of 0·5 microsec., and a back such that the time to half maximum value measured from the instant the voltage was 0·1 of the maximum value on the front, was 5 microsec. The amplitude was adjusted just to spark-over a gap of 300 mm. between 750-mm. diameter spheres; a series of oscillograms of this wave was made, using values of R_1 ranging from 6 000 to 55 000 ohms. The value of R_2 was also varied to obtain a convenient recorded amplitude. The length of the front, and the amplitude of the recorded wave, are plotted as functions of R_1 in Fig. 3. The corresponding theoretical error curves are shown by the dotted lines in Fig. 3 where the experimental and theoretical curves are made to coincide at zero value of R_1. The agreement between the slopes of the theoretical and experimental curves is reasonably good.

The value of R_1 was determined, before and after a record was taken, at low voltage with the aid of an audio-frequency bridge circuit. The maximum average stress on the electrolyte constituting R_1 was of the order of 3 kV per cm. The change in conductivity at this stress from that at low voltages* is negligibly small.

* M. Wien: *Annalen der Physik*, 1927, vol. 83, p. 327.

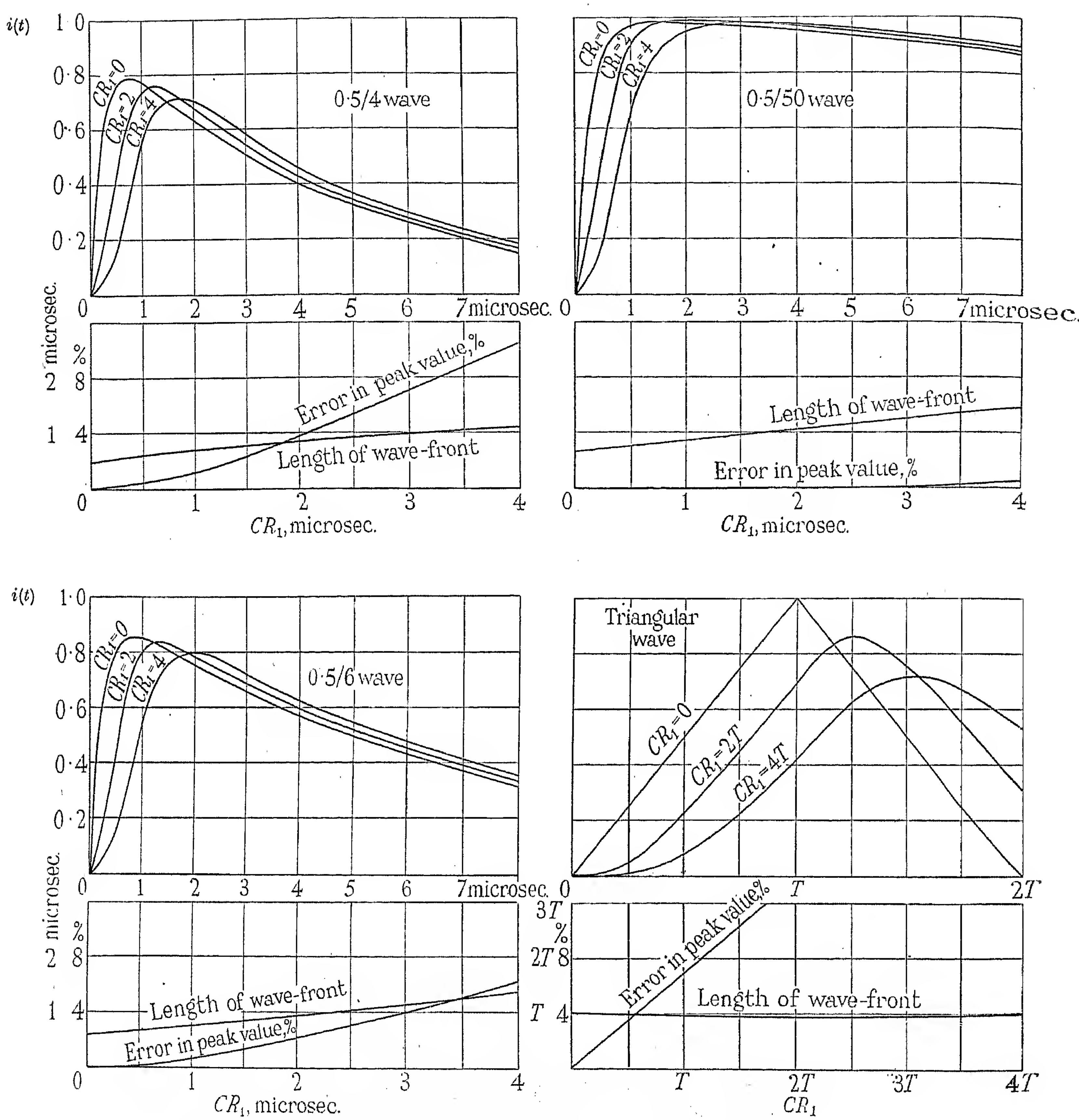

Fig. 2.—Theoretical response curves of resistance divider, derived from equation $i(t) = \int_0^t F_1'(\lambda)F_2(t-\lambda)d\lambda$

$$\text{where } F_1(t) = 1 + 2\sum_{m=1}^{m=\infty}(-1)^m \frac{-m^2\pi^2}{CR_1}.$$

$$F_2(t) = e^{-\alpha t} - e^{-\beta t}$$

Top left-hand curve: $\alpha = 0{\cdot}23$, $\beta = 4$
Top right-hand curve: $\alpha = 0{\cdot}014$, $\beta = 4$
Lower left-hand curve: $\alpha = 0{\cdot}014$, $\beta = 4$
$\times 10^6$

For different values of V the voltage v applied to the ordinate plates of the oscillograph was maintained approximately constant by varying the value of R_2.

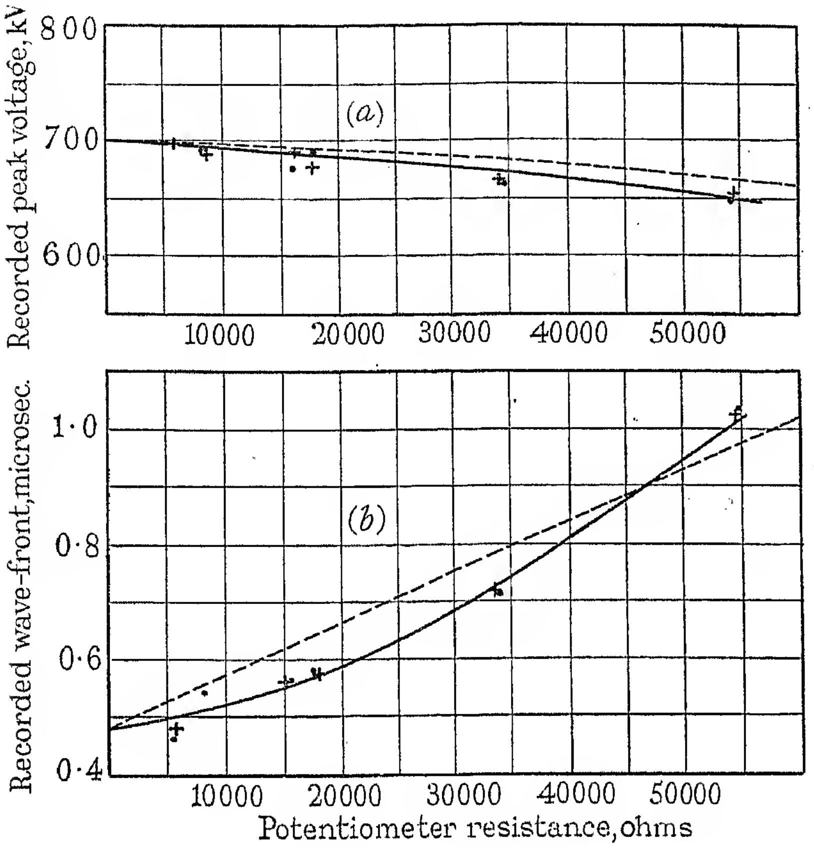

Fig. 3.—Relation between potentiometer resistance and recorded values of:—

(a) Peak voltage of impulse } for 0·5/5 wave.
(b) Length of wave-front }

+ Positive polarity.
. Negative polarity.

The sensitivity of the ordinate plates was about 40 volts per mm., and by means of electrostatic biasing circuits a deflection of approximately 50 mm. could be recorded. The deflectional sensitivity of the oscillograph is inversely proportional to the accelerating voltage, which was regulated by resistance in the primary circuit of the supply transformer. A calibrating voltage measured with an electrostatic voltmeter was recorded. Typical oscillograms recording the flashover of a sphere-gap with positive and negative impulse voltages are reproduced in Fig. 4.

To determine the voltage v from the oscillograph record required the measurement of two deflections, one corresponding to the breakdown voltage and the other to the calibrating voltage. Each of these deflections could be measured to an accuracy of $\frac{1}{2}$ %. Allowing $\frac{1}{2}$ % for error in the setting of the calibrating and of the accelerating voltages, the possible error in the determination of v is approximately 2 %. The possible errors in deriving V from v are estimated to be $\frac{1}{2}$ % in adjusting the generator to flash-over the gap in 90 % of the applications of voltage, and $\frac{1}{2}$ % due to uncertainty in the value of R_1 (the value of R_1 was chosen so that errors due to earth capacitance were negligible), making a total possible error, neglecting any uncertain systematic errors, of 3 %. The probable error in the determination of the flashover voltage for a given setting arising from these unsystematic errors can be reduced to about 1 % by averaging the results of a sufficient number of observations.

(c) Polarity effects

Experiment shows that, in general, impulse flashover occurs between two electrodes most readily when the field at the positive electrode is strongest. If the electrodes are similar in form, and one is earthed, then the field at the high-voltage electrode should be greater than that at the other electrode owing to the neighbourhood of earth or earthed objects. In a uniform field no polarity effect obtains.*

To determine under what conditions polarity effect occurred, the gaps were flashed-over with power-frequency voltage, and the half-cycle in which the discharge occurred was observed by means of the cathode-ray oscillograph. An antenna located near the sphere-gap conveyed an impulse voltage to the auxiliary circuits of the oscillograph at the instant of sparkover of the

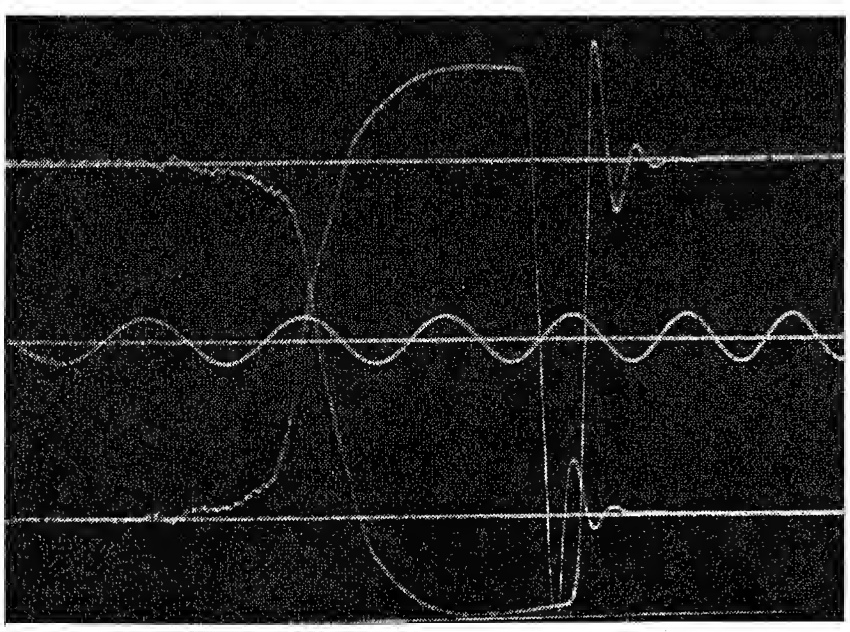

Fig. 4.—Typical oscillogram of minimum impulse sparkover voltage of sphere-gap with positive and negative waves.

* W. O. Schumann: "Electrical Breakdown Strength of Gases," p. 141.

gap. The voltage applied to the gap was raised continuously from zero to the flashover value in approximately 5 sec. A typical oscillogram indicating breakdown in the negative half-cycle, and recording the subsequent current through the gap, is reproduced in Fig. 5, and the results obtained showing the percentage of flashover occurring in the positive half-cycle for various values of the ratio s/d, and for spheres of various sizes, are given in Table 3.

From the relation between impulse flashover voltage and the ratio s/d determined for positive and negative polarities the minimum value of s/d showing the polarity effect was determined, and tabulated in the last column of Table 1 for spheres of different diameters. In each case where a polarity effect was present, the positive flashover was higher than the negative. In Table 2 the magnitude of the polarity effect at a value of s/d of 0·5 is given. The results obtained by the present authors can be compared with those of the other workers already mentioned by an examination of Tables 1 and 2.

The value of s/d at which the positive and negative impulse flashover values begin to diverge is approximately 0·2 for small and 0·3 for large spheres. The value of s/d where the power-frequency flashover changes over from occurring predominantly in the positive half-cycle to the negative half-cycle is approximately 0·4 for small spheres and 0·8 for large spheres. At values of s/d where the polarity effect is first observed with impulse voltage, Table 3 shows that the power-frequency flashover occurs most easily in the positive half-cycle. These results indicate that the behaviour of the gap is different according to whether the voltage is impulsive or alternating at power frequencies, and that the performance with impulse voltages cannot be deduced from that at power frequencies.

The effect on the flashover characteristics of the gap of modifications in the circuit set-up was investigated by the following experiments carried out with spheres of 1 000-mm. diameter: (i) Normal circuit set-up. (ii) The upper sphere was earthed instead of the lower. (iii) An earthed metal sheet 3 ft. × 8 ft. (90 cm. × 250 cm.) was mounted with the long side vertical and symmetrical with respect to the spheres, at a distance of 1·5 m. from the surface of the spheres. (iv) As arrange-

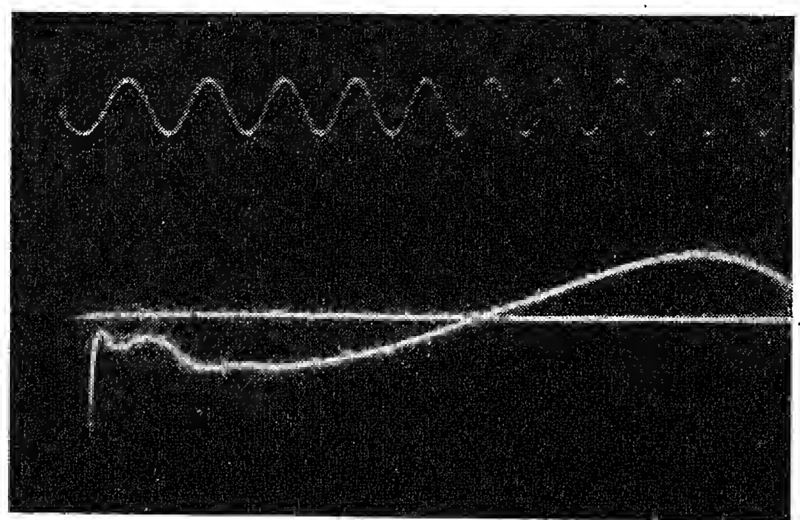

Fig. 5.—Oscillogram of power current through arc immediately after breakdown of sphere-gap on alternating current.

Table 3

Ratio s/d	Percentage of flashovers occurring in the positive half-cycle for spheres of diameter in millimetres of:—				
	1 000	750	500	250	125
0·1	12	56	62	48	30
0·2	56	82	88	74	90
0·3	90	94	92	62	84
0·4	100	92	62	30	50
0·5	90	80	0	10	30
0·6	70	60		0	15
0·7					4
0·8				0	0

Table 4

Arrangement number	Spheres 1 000-mm. diameter: percentage deviation from flashover value obtained with normal set-up	
	Positive	Negative
	Gap 500 *mm.*	
(ii)	− 3·5	− 2·5
(iii)	− 4·0	− 2·5
(iv)	− 5·5	− 3·0
	Gap 300 *mm.*	
(ii)	− 1·0	− 1·5
(iii)	− 0·5	− 1·5
(iv)	− 0·5	− 1·5

ment (iii), but with the sheet mounted at a distance of 1 m. from the surfaces of the spheres.

The results, given in Table 4, show that drastic modifications in the set-up of the gap are necessary to produce changes of 5 % in the flashover characteristics of the gap for spacings up to the radius.

(d) Effect of Wave-Shape

Most of the tests were carried out with aperiodic waves with fronts of approximately 0·5 microsec., and falling to half maximum value in 20 microsec. Some tests were carried out on the 1 000-mm. and 125-mm. sphere-gaps in which similar wave-shapes were used except that the times to half maximum value on the back of the wave were respectively 5 microsec. and 100 microsec. No difference in the minimum impulse flashover voltage was obtained for these extremes of wave-shape.

The authors have found that the sphere-gap is not suitable for the measurement of voltage when breakdown occurs on the front of the wave.

(e) Minimum Impulse Flashover Values

The minimum impulse flashover voltage of sphere-gaps for spheres of various diameters, and for various values of the ratio s/d, are given in Table 5. The results have been corrected to correspond to an air temperature of 20° C. and a barometric height of 760 mm. of mercury; the flashover voltage is assumed to be inversely proportional to the absolute temperature and directly proportional to the pressure for the range of atmospheric conditions occurring throughout the tests.

The results are given in the form of smoothed curves in Fig. 6, the variables used being the ratios V/d (kilovolts per mm.) and s/d. Different families of curves are plotted for positive and for negative impulse and power-frequency voltages. In Fig. 7 the ratio V/d is plotted as a function of the diameter of the spheres for different values of s/d. By extrapolating these curves the impulse flashover characteristics for spheres of larger diameters than those tested can be estimated; the flashover characteristics for 2 000-mm. spheres with similar set-up should be capable of deduction from these curves to an accuracy of 2 %.

Table 5

Ratio s/d	Minimum impulse flashover voltage (kV, peak) corrected to atmospheric conditions, viz. 20° C. and 760 mm. of mercury									
	Sphere diameter, in mm.									
	1 000		750		500		250		125	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
0·1	264	264	200	200	139	139	75	75	41·0	41·0
0·2	513	513	384	384	267	267	142	142	77·5	77·5
0·3	740	732	550	550	378	378	201	201	110·5	108·5
0·4	936	916	696	687	482	476	254	249	139	135
0·5	1 100	1 065	824	800	570	557	299	289	164	157
0·6	1 225	1 175	920	880	645	625	335	319	184	174

(4) POWER-FREQUENCY MEASUREMENTS

To extend the data on sphere-gap performance, tests were carried out with power-frequency voltages. The methods of measurement have been previously described.*

For voltage measurements up to 400 kV (peak) the standard of reference was a shielded compressed-gas condenser. Beyond this voltage and up to 600 kV (peak) a shielded sphere-gap was used at two different spacings, calibrated at 400 kV against the gas condenser. The measurements with the two spacings agreed, and so were taken to be correct. For voltages beyond 600 kV the curve giving the ratio of the testing transformer as a function of the primary exciting voltage was extrapolated. The accuracy of this extrapolation was estimated to be within 2 %.

Table 6

Ratio s/d	Power-frequency flashover voltage (kV, peak) corrected to atmospheric conditions, viz. 20° C. and 760 mm. of mercury				
	Sphere diameter, in mm.				
	1 000	750	500	250	125
0·1	260	195	134	71·0	38·2
0·2	505	376	257	135	72·8
0·3	720	534	363	191	103·0
0·4	890	665	453	237	128·5
0·5	1 025	769	525	275	149
0·6		844	575	303	162

The tests were made at a frequency of 50 cycles per sec. with a test voltage the wave-shape of which was approximately sinusoidal. The voltage was raised quickly to approximately 80 % of the flashover value, and then slowly until flashover occurred. The values recorded are the average of a large number of observations.

No attempt was made to avoid corona, owing to the difficulties of the problem at the highest voltages. An

* R. Davis, G. W. Bowdler, and W. G. Standring: *Journal I.E.E.*, 1930, vol. 68, p. 1222.

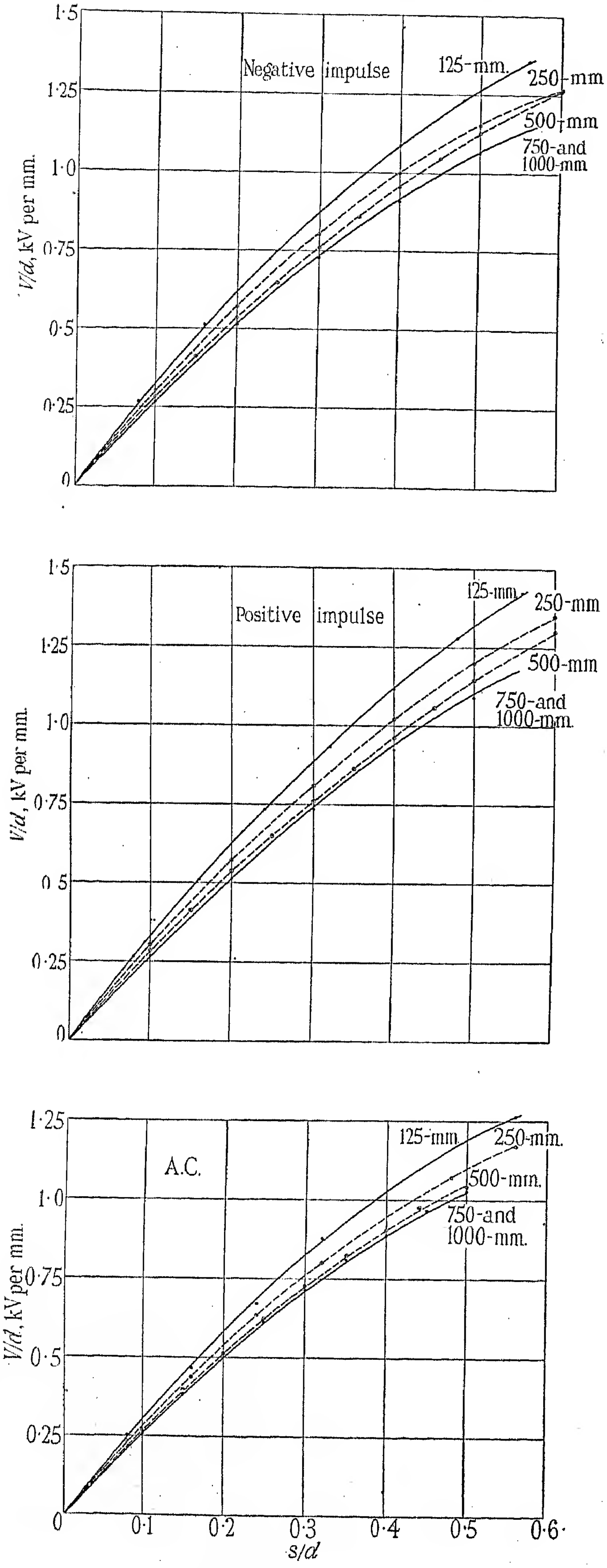
Negative impulse
125-mm.
250-mm
500-mm
750-and 1000-mm
Positive impulse
125-mm.
250-mm
500-mm
750-and 1000-mm.
A.C.
125-mm
250-mm.
500-mm.
750-and 1000-mm.
V/d, kV per mm.
s/d

Fig. 6

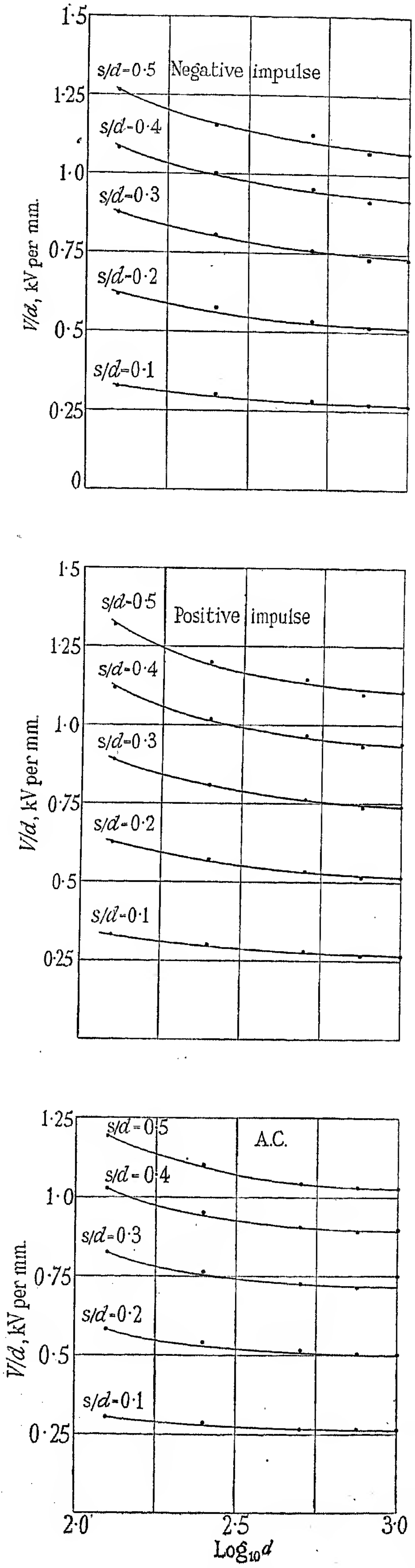
Negative impulse
s/d=0·5
s/d=0·4
s/d=0·3
s/d=0·2
s/d=0·1
Positive impulse
A.C.
V/d, kV per mm.
Log10 d

Fig. 7

examination of the curves in Figs. 6 and 7 gives no indication of any modification in the general characteristics of the curves which might be expected if corona were modifying the flashover characteristics of the larger spheres. The corona in the set-up is much less for the impulse tests than for the power-frequency tests; in the case of both the impulse and the power-frequency measurements the curves relating v/d to s/d approach a limiting position. Any appreciable effect due to corona should be indicated by a widening separation between these curves with increasing values of the diameter.

The results obtained are given in Table 6 and in the curves of Figs. 6 and 7.

Table 7

Ratio s/d	Percentage difference of impulse from power-frequency flashover values for spheres of diameter (in mm.) of:—									
	1 000		750		500		250		125	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
0·1	1·5	1·5	2·5	2·5	4·0	4·0	5·0	5·0	7·0	7·0
0·2	1·5	1·5	2·0	2·0	4·0	4·0	5·0	5·0	8·0	8·0
0·3	2·5	1·5	3·0	3·0	4·0	4·0	5·5	5·5	7·5	5·5
0·4	5·0	3·0	4·5	3·5	6·5	5·0	7·0	5·0	8·5	5·5
0·5	7·5	5·0	6·0	4·0	8·5	6·0	8·5	5·0	10·0	5·5
0·6			9·0	4·5	12·0	8·5	9·5	5·5	13·5	7·5

Table 8

Ratio s/d	Percentage difference from values given in Tables 5 and 6 of the results of previous workers* for spheres of diameters (in mm.) of:—									
	1 000		750		500		250		125	
	A	B	A	B	A	B	A	B	A	B
	(i) *Impulse voltages, positive polarity*									
0·1	+ 1·5	+ 0·5	+ 0·5	+ 2·0	− 0·5	− 5·0	− 5·0	− 2·0	− 7·0	− 5·0
0·2	+ 0·5	+ 0·5	+ 1·5	0·0	− 0·5	− 1·0	− 2·5	− 2·5	− 6·0	− 7·0
0·3	− 1·0	− 2·5	+ 1·5	+ 1·0	+ 1·0	0·0	0·0	− 0·5	− 4·0	− 6·0
0·4	− 2·5	− 4·5	+ 0·5	0·0	+ 0·5	− 0·5	− 0·5	+ 1·0	− 4·0	− 3·5
0·5	− 5·5	− 5·5	− 2·5	− 3·0	− 2·0	− 3·0	+ 0·5	+ 2·0	− 3·5	0·0
0·6	− 7·0	− 6·0	− 3·5	− 6·0	− 4·0	− 5·5	0·0	+ 2·5	− 2·5	
	(ii) *Impulse voltages, negative polarity*									
0·1	+ 1·5	+ 0·5	+ 0·5	+ 2·0	− 0·5	− 5·0	− 5·0	− 2·0	− 7·0	− 5·0
0·2	+ 0·5	+ 0·5	+ 1·5	0·0	− 0·5	− 1·0	− 4·0	− 2·5	− 6·0	− 6·0
0·3	− 3·0	− 2·5	− 2·0	− 3·0	− 0·5	− 2·5	− 4·0	− 1·5	− 6·0	− 4·5
0·4	− 4·5	− 4·5	− 2·0	− 4·5	− 3·0	− 4·0	− 2·5	− 1·0	− 6·0	− 4·0
0·5	− 6·0	− 6·0	− 3·5	− 5·5	− 4·5	− 6·0	− 2·0	− 1·5	− 5·0	− 4·0
0·6	− 6·5	− 7·0	− 4·0	− 5·0	− 5·5	− 8·0	− 1·5	− 1·0	− 3·0	
	(iii) *Power-frequency voltages*									
0·1	+ 3·0	+ 1·5	+ 3·5	+ 4·5	+ 3·5	− 1·5	0·0	+ 3·0	− 0·5	+ 1·5
0·2	+ 1·5	+ 2·0	+ 3·5	+ 0·5	+ 3·5	+ 2·5	+ 0·5	+ 2·5	− 1·0	− 0·5
0·3	− 1·5	− 1·0	+ 1·0	− 1·5	+ 2·5	+ 1·5	+ 1·0	+ 3·5	− 1·0	+ 1·0
0·4	− 1·5	− 2·0	+ 1·0	− 3·0	+ 2·0	+ 0·5	+ 2·0	+ 3·0	− 1·0	+ 1·5
0·5	− 2·5	− 2·0	0·0	− 3·5	+ 1·0	0·0	+ 3·0	+ 3·5	0·0	+ 1·0
0·6			0·0	− 2·5	+ 2·5	0·0	+ 3·5	+ 4·0	+ 4·0	

* A = Bellaschi and McAuley (*Electric Journal*, 1934, vol. 31, p. 228). B = Meador (*Electrical Engineering*, 1934, vol. 53, p. 942).

The flashover values obtained with power frequency are lower than the corresponding impulse figures. In Table 7 the difference between the impulse and the power-frequency figures are tabulated as a percentage of the power-frequency value. The differences have

been rounded off to the nearest 0·5 %, and in every case the sign is positive and has been omitted.

Previous workers have found that the negative-impulse and the power-frequency flashover values are the same. Table 7 shows that with increasing values of s/d the negative figures deviate less than the positive. This generalization holds for the 750-mm. and 1 000-mm. spheres, even though Table 3 shows that the majority of sparkovers at values of s/d ranging from 0·2 to 0·6 for these sizes of spheres occurred in the positive half-cycle of the power-frequency wave. Table 7 shows further that the differences tabulated tend to increase with decreasing sphere diameter.

The power-frequency and the impulse figures were obtained by different methods, and with different set-ups. In the absence of any (undetected) systematic errors occurring in either or both sets of tests the results point to the conclusion that, under normal conditions of minimum impulse flashover with usual test wave-shapes, the sphere-gap has an impulse ratio which may be as much as 1·09 for negative and 1·14 for positive waves in the range of values of s/d up to 0·6.

(5) COMPARISON WITH RESULTS OBTAINED BY PREVIOUS WORKERS

The results obtained are compared in Table 8 with those given by the American workers. The results of Dattan are not included in the comparison, as he used spheres mounted horizontally. The differences given to the nearest 0·5 % are recorded as percentages of the values given in Tables 5 and 6.

The figures given in Table 8 show that the agreement is much better for the power-frequency figures than for the impulse figures. Thus, for values of s/d up to 0·6, 50 % of the American observations are within 2 % of the corresponding values obtained by the authors, while 90 % are within 4 %. For positive impulse voltages, 50 % of the observations are within 3 % and 90 % are within 7 %; while, for negative impulse voltages, 50 % of the observations are within 4 % while 90 % are within 7 %.

(6) ACKNOWLEDGMENTS

The authors wish to express their thanks to their colleagues, Dr. Rayner and Mr. Standring; to the first for his interest and encouragement, and to the second for many valuable criticisms and suggestions during the course of both the experimental work and the preparation of the paper. The authors' thanks are also due to the Director, National Physical Laboratory, for permission to publish the results of the investigation.

APPENDIX

Calculation of the Current Flowing from the Earthed End of a Resistance R_1 with Uniformly-Distributed Capacitance C to Earth

The current at the low-voltage end is given by

$$i = \frac{V}{R_1} \cdot \frac{a}{\sinh a} \quad . \quad . \quad . \quad . \quad (1)^*$$

where $a^2 = pCR_1$. Let $Z(p) = \sinh a$, and let p_m be a solution of the equation $Z(p) = 0$. Then

$$i = \frac{V}{R_1}\left[1 + \sum \frac{ae^{p_m t}}{p_m Z'(p_m)}\right] \quad . \quad . \quad . \quad (2)$$

Now $Z'(p) = \cosh a \cdot \dfrac{da}{dp} = \cosh a \cdot \dfrac{CR_1}{2a}$

Let $a = jb$.

Then $Z(p) = \sinh a = \sinh jb = j \sin b$

For $Z(p) = 0$, we have $j \sin b = 0$, the general solution of which is:—

$b = m\pi$ . . . where m can have the values 1, 2, 3, . . . etc.

Hence $a = m\pi j$

whence $a^2 = p_m CR_1 = -m^2\pi^2$

and $p_m = \dfrac{-m^2\pi^2}{CR_1}$

and $\cosh a = \cosh jb = \cos m\pi = (-1)^m$

Substituting in equation (2) gives the required expression, namely

$$i = \frac{V}{R_1}\left[1 + 2\sum_{m=1}^{m=\infty}(-1)^m e^{-\frac{m^2\pi^2 t}{CR_1}}\right]$$

* See R. Davis: *Journal of Scientific Instruments*, 1928, vol. 5, p. 307.

[The discussion on this paper will be found on page 669.]

THE CALIBRATION OF THE SPHERE SPARK-GAP FOR VOLTAGE MEASUREMENT UP TO ONE MILLION VOLTS (EFFECTIVE) AT 50 CYCLES

By F. S. EDWARDS, B.Sc., Associate Member, and J. F. SMEE.

(*Paper first received* 31*st May, and in revised form* 29*th November,* 1937; *read before the* METER AND INSTRUMENT SECTION 7*th January,* 1938.)

SUMMARY

Since the issue of B.S.S. 358 in 1929 on the "Measurement of Voltage with Sphere-Gaps," a number of calibrations of the sphere spark-gap have been put forward in Germany and the United States, but these differ appreciably amongst themselves and, moreover, are usually restricted to voltages of the order of 500 kV(eff.) and to spheres of 75 cm. diameter or less.

The present paper is still another contribution to the literature on the subject, its justification being that it contains calibrations for larger spheres and at higher voltages than have hitherto been obtainable in this country.

After a brief review of existing information the calibration at 50 cycles (a.c.) of a range of sphere spark-gaps is discussed in detail; methods of absolute measurement of high voltages are described, and calibrations are put forward for spheres up to 200 cm. diameter at voltages up to 1 million volts (effective) with one sphere earthed. These calibrations are based on a method of voltage measurement which is believed to be unique.

Some attention has been directed towards the determination of the polarity of the high-voltage electrode when breakdown occurs, in view of the obvious importance of this feature in its relation to the breakdown of asymmetrical gaps under direct and impulsive voltages. A new type of polarity indicator is described.

A correlation was observed between the noise of the spark and the polarity of the high-voltage electrode at breakdown.

The effect of irradiation of the gap with radium and by other means is described.

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(1) INTRODUCTION

The literature on the subject of the breakdown of the sphere spark-gap in air is now so enormous that it might seem hardly possible to add anything further of interest or importance to our existing knowledge. As, however, within the last 12 months proposals made by one eminent body* have not agreed with the test results of another, equally eminent,† it is apparent that the last word on the subject has not yet been said, and that there is still scope for original investigational work and critical analysis.

While disclaiming any intention of attempting to write a full and final statement on the matter, therefore, the authors have put forward certain data which the experimental facilities at their disposal have permitted them to gather, in the hope that they will throw a little more light on the problem of sphere spark-gap calibration, especially at the higher voltages where information is still scanty.

(2) REVIEW OF PREVIOUS WORK

The sphere gap as a means of measuring high voltages is of considerable antiquity, judged by the standards of age which are applicable to electrical engineering. Baille‡ showed in 1882 that the relationship between breakdown voltage and spacing is not linear, and in 1889 Wolf§ demonstrated that the atmospheric pressure influenced the results. Later investigators with more refined methods of measurement detected the effect of features such as temperature, surface condition of the electrodes, and adjacent conductors, while the significance of the

* See Bibliography, (1). † *Ibid.*, (2). ‡ *Ibid.*, (3). § *Ibid.*, (4).

polarity of the applied voltage in its effect on the breakdown value was recognized by 1892.*

Lengthy formulae with sufficient theoretical justification to render them plausible began to appear by 1911, and the subject of the evaluation of a satisfactory expression was pursued with more enthusiasm than success for a number of years. No formula, however, has stood the test of agreeing with experimental values when extrapolated. Peek† was the first to make a comprehensive study of the whole problem, and his book was regarded for many years as the last word on the subject.

Since the War the development of high-voltage transmission has focused attention on the calibration of spheres for the accurate measurement of voltages of the order of 1 or 2 million volts, and the discrepancies between calculated and observed results have become very serious at the higher voltages. The current British Standard Specification No. 358—1929, at present under revision, is limited to 800 kV(eff.) with 75-cm. spheres at 75 cm. spacing, and while the V.D.E. rules of 1926 contain a calibration for 100-cm. spheres up to 835 kV(eff.), in addition to figures for the smaller sizes of sphere, both these specifications are known to be in error by about 10 % at the higher voltages.

The most recent comprehensive tables are those of the A.I.E.E.‡ published in 1936; these include figures for spheres up to 200 cm. diameter and voltages up to $2\frac{1}{2}$ million volts (peak).§

(3) STATEMENT OF THE PROBLEM OF CALIBRATION

The term "calibration" as applied to an air spark-gap may imply one of two operations:—

The first is the calculation on purely theoretical grounds of the breakdown voltage of a gap between two electrodes of given shape. If this can be done it is obvious that a calibration curve can be drawn which will enable the air-gap to be used as a *primary* standard of voltage measurement so that other types of voltmeter of a continuously indicating nature can be calibrated from it.

It has been found that such calculations are quite impossible, experience having repeatedly shown that some seemingly simple and rational formula which represents with sufficient accuracy the course of a breakdown-voltage/spacing curve over a certain range invariably fails to agree with observed results when it is extrapolated. If a new term is added to the expression to correct the divergence and the curve is again extrapolated the discrepancy appears once more.

These divergencies are always in the same direction, the calculated figures being higher than the observed values of breakdown voltage in every case. As recently as 1934 Meador‖ ventured to extrapolate a curve for 200-cm. spheres from a 50-cm. spacing to a 200-cm. spacing, but his figures, although lower than Peek's calculated values by 13 % at the maximum spacing, were apparently considered to be still too high, as the A.I.E.E. revised sphere-gap values referred to previously¶ (also extrapolated) were another 2 % lower.

* See Bibliography, (5). † *Ibid.*, (6). ‡ *Ibid.*, (7).
§ In the preparation of this review the authors have drawn largely upon Müller's summary in the *Elektrotechnische Zeitschrift* (1935, vol. 56, p. 1379).
‖ See Bibliography, (8). ¶ *Ibid.*, (7).

An authoritative pronouncement on the true values for these spheres must seemingly await the construction of a reliable voltmeter reading up to $2\frac{1}{2}$ million volts.

As the theory of the field in a sphere spark-gap has been extensively studied it is not intended to discuss it at all in this paper, but merely to point out that the theoretically devised expressions have had to be repeatedly modified, first to take account of the fact that the apparent electric strength of air is a function of the curvature of the electrode surface, and secondly to allow for the effect on the field distribution of a testing laboratory of finite dimensions.

If absolute calibration is impossible the spark-gap becomes essentially a secondary standard, and calibration can then be divided into two distinct sections:—

(1) Provision of some other (absolute) means of measuring the voltage,

(2) Calibration of the spark-gap against the absolute voltmeter,

and this paper is mainly devoted to a detailed description of these two operations.

(4) ABSOLUTE VOLTAGE MEASUREMENT ON ALTERNATING CURRENT AT 50 CYCLES

A large number of methods of voltage measurement have been proposed from time to time, and it is outside the scope of this paper to discuss them in detail, but a brief reference to some of them will perhaps be useful in enabling their value to be assessed, and they are dealt with below.

The neon-tube voltmeter with potential divider has been discussed fully by Ryall* who, however, restricted himself to a maximum voltage of 110 kV(eff.), and gave no information regarding the measurement of the capacitance of his high-voltage condenser, which was apparently regarded as constant.

The resistance voltmeter offers some attractive features, but stray capacitance and inductance effects make it useless as an absolute instrument. The variation of its characteristics with voltage might be expected to be slight, and it could therefore be used over a certain range as a reliable secondary standard, but considerations of size and cost make its application to voltages of the order of 1 million almost impracticable. A knowledge of the crest factor of the voltage wave is also necessary.

The attracted-disc electrometer, ellipsoid voltmeter, and capacitance potential divider combined with an electrostatic voltmeter, all provide alternative means of absolute measurement.

The use of the crest voltmeter, first proposed by Chubb and Fortescue in 1913,† has been discussed in considerable detail by Davis, Bowdler and Standring,‡ and other experimenters, but again no attempt appears to have been made to determine the variation of the capacitance of the high-voltage condenser with voltage, although all other possible sources of error seem to have been thoroughly explored.

As the alternating-voltage measurements described in the present paper were made with the crest voltmeter, and as the accuracy of the results is necessarily dependent upon a precise knowledge of the capacitance of the air condenser employed, a careful determination was made

* See Bibliography, (9). † *Ibid.*, (10). ‡ *Ibid.*, (11).

by special means in order to ascertain its value over the whole range of voltage of the transformers with which it was associated. The means employed were original, as far as is known, and involved a series of successive calibrations as explained below. The high-voltage testing circuit used for this purpose consisted of two 500-kV transformers coupled in the Dessauer cascade connection, the tank of the second transformer being insulated from earth for 500 kV on large cylindrical bakelite-paper columns. Each transformer is provided with a condenser-type terminal bushing with a buried low-voltage foil insulated from earth which can be used for connection to a crest voltmeter circuit if required. The standard air condenser on which reliance is placed for measurements up to 1 million volts (eff.) is mounted above the terminal bushing of the second transformer and consists of two large, horizontal, flat discs (20 ft. diam.) with rounded edges of 2 ft. radius, one of which is attached to the bushing conductor, the other being supported from the roof directly over the lower electrode. The distance between the discs is 11 ft. The discs are constructed of expanded metal, mounted on an angle-iron framework, and coated with plaster, rubbed down, and then treated with a conducting paint. The upper electrode is in two parts and consists of a central disc 10 ft. diameter which is insulated lightly from the outer and rounded portion which forms the guard ring and is earthed. The central disc is connected to the rectifier system on the control desk by means of a completely screened lead.

The rectifier is of the mechanical type with negligible voltage drop across it and the measuring instrument is a moving coil Weston Laboratory Standard milliammeter with a large scale and reading 1 mA full scale. This is shunted by a resistance of such value that it reads 0–1 000 kV directly, although, as explained later, a correction is necessary to allow for the voltage-variation of capacitance of the air-condenser.

For the purpose of the determination of the capacitance of the condenser the following means were adopted. A compressed-gas condenser was available for use up to 225 kV(eff.) and its capacitance was measured with great care over the whole working range in comparison with that of another air condenser of different construction working at atmospheric pressure, in which the electrodes were concentric, by means of the Schering bridge. Both condensers were effectively screened, and as no difference in the power factor or capacitance of either of them relative to the other could be detected at any voltage, it was assumed that the power factor of each was zero, and hence that there was no brushing from the active part of either condenser. From this it was concluded that the capacitance was constant and calculable from the physical dimensions of the condenser. The only slight uncertainty arose from the inevitable narrow gap between the guard rings and the main electrode, but this was known to be of very small magnitude ($\frac{1}{16}$ in.) and on actual measurement at a low voltage the capacitance agreed within $0 \cdot 1$ % with the calculated value.

The next step was to determine the capacitance of each terminal bushing at various voltages up to 225 kV. This of course presented no difficulty on the Schering bridge, with the compressed-gas condenser as a standard. A measurement was also made of the capacitance of the million-volt plate condenser under three conditions:—

(*a*) With the second 500-kV transformer used for excitation, its tank being therefore earthed.

(*b*) With the transformers in the cascade connection, so that the tank of the second transformer was at half the voltage impressed on the condenser.

(*c*) With the first (i.e. permanently earthed) 500-kV transformer used for excitation, the second transformer being short-circuited, with its tank thus at the test voltage. In this case one of the leads to the primary winding of this second transformer was temporarily disconnected, for obvious reasons.

Three practically parallel straight lines connecting capacitance with voltage were obtained in this way. They were equally spaced, and showed an increase in the capacitance of about $0 \cdot 25$ % as the voltage was raised from 100 to 225 kV, while the capacitance at any one voltage increased with the voltage on the tank of the second transformer, being lowest under condition (*a*) (tank earthed), 1 % higher under condition (*b*) (tank at half voltage), and 2 % higher under condition (*c*) (tank at full voltage).

The next step was to arrange crest-voltmeter circuits on each transformer. For the first transformer this of course presented no difficulty, but for the second it was necessary to mount the instrument and rectifiers (suitably screened) on the tank, the readings being taken through a telescope. The transformers were connected in cascade and readings taken of the individual transformer voltages and also of the total voltage to earth up to 1 million volts. With the aid of the mechanical rectifier it was established that the phase angle between the two component voltages was so small that any error involved by their direct addition was completely negligible.

By direct means it was also possible to compare the two individual 500-kV crest voltmeters with the million-volt crest voltmeter up to 500 kV, so that the true voltage to earth and hence the capacitance of the plate condenser could be calculated up to 450 kV, which was the limit beyond which no direct knowledge was available of the component voltages.

Measurements were next made of the bushing capacitances against the air condenser as a standard up to 500 kV, and it was now possible to calibrate the two crest voltmeters up to 450 kV and thence to calculate the plate condenser capacitance up to 900 kV. Two other calculations, viz. calibration of the two crest voltmeters up to 500 kV, and thence the calculation of the plate condenser capacitance up to 1 million volts, completed the work.

Cross checks were applied where possible, the capacitance measurement of the bushings against the plate condenser at voltages up to 225 kV being directly compared with the figures obtained by measurement of the bushings against the standard compressed-gas condenser.

Actually a number of small discrepancies were found, and were traced to the influence of the temporary high-voltage leads which had necessarily to be used; means were devised for determining their magnitudes and allow-

ing for their effects. The effect of the leads was to distort the field in the neighbourhood of the million-volt air condenser, and to increase its capacitance slightly. The magnitude of the change was determined by a measurement of the capacitance against that of the bushing of the second transformer with and without the leads in position.

It will be seen that this method avoids the necessity for the extrapolation of any curve except (1) the capacitance/voltage curve of the compressed-gas condenser, for which very strong evidence exists as to its linear nature, and (2) the plate condenser capacitance/voltage curve from 225 to 500 kV for the conditions (*a*) and (*c*) above. Here the variation of the capacitance with voltage was known for condition (*b*), and as the capacitance under this condition was a linear function of the voltage up to 450 kV, and as the capacitance-voltage curves under the other two conditions were straight lines close to and parallel to the line for condition (*b*) over the range 0–225 kV, it was assumed that a linear extrapolation could safely be made. It had also to be assumed that the capacitance of the bushing of No. 2 transformer was unaffected by the tank voltage. This is considered to be justified because its capacitance is about 20 times that of the plate condenser, and as the effect of the tank voltage on the plate condenser capacitance is to alter it by not more than 2 % the effect of field distortion on the bushing capacitance is regarded as negligible.

A number of possible errors remain:—

(1) The earth capacitance of the screened lead from the top plate of the air condenser to the rectifier is about 1 600 $\mu\mu$F. The maximum voltage on this lead is 5 volts, and at 50 cycles this corresponds to a shunted current of $2 \cdot 5\ \mu$A in quadrature with the current of approximately 5 mA flowing through the rectifier and it can therefore be entirely neglected. The error due to this cause from high harmonics might in some cases be serious, but analysis of the wave-shape of the transformers showed that while it was not quite sinusoidal there was no harmonic present which could possibly affect the results. Confirmation of this conclusion was obtained from the fact that when an additional condenser of 20 000 $\mu\mu$F capacitance was placed across the rectifier system and instrument not the slightest difference could be detected in the deflection at 500 kV.

(2) Any difference in phase between the voltages of the two cascade-connected transformers would make the apparent capacitance of the plate condenser too low and the instrument would therefore read high. As stated previously, the phase difference was so small that the error due to this cause was well under $0 \cdot 1$ % and was therefore ignored.

(3) Errors in frequency result in a proportional voltmeter error. The frequency was indicated by a vibrating-reed instrument capable of showing variations of $\pm \frac{1}{4}$ cycle, or $\pm\, 0 \cdot 5$ %. This error only arose during the actual breakdown tests on the sphere-gaps, as the Schering-bridge readings were unaffected by it and the comparative readings on the crest voltmeters which were read simultaneously during the tests on the plate condenser were of course all influenced to precisely the same extent by frequency errors. By a careful watch it was usually possible to control the frequency at the instant of breakdown to within something less than $\pm\, 0 \cdot 5$ % and if it exceeded these limits the reading was neglected.

(5) CALIBRATION OF THE SPHERE SPARK-GAP ON ALTERNATING CURRENT AT 50 CYCLES

(a) Testing Set and Series Resistance.

The testing equipment available consisted of two 1 000/500 000-volts, 500-kVA, 50-cycle transformers which could be used independently or coupled together in the Dessauer cascade connection. A 1 000-volt, 1 000-kVA generator driven by a d.c. motor was used for excitation, voltage control being effected on the field of the exciter of the generator. As stated previously and as can be seen from Fig. 1 (see Plate, facing page 660), the plate condenser upon which reliance is placed for voltage measurement is mounted on top of the bushing of the second transformer and is thus high in the air and well removed from extraneous influences arising from the movement of objects on the floor of the laboratory.

A permanent resistance of $0 \cdot 132$ ohm is included in the generator circuit, and when one transformer only was in use an additional resistance of $1 \cdot 65$ ohms was inserted. The high-voltage resistance consisted at first of a water tube, but this was later replaced by a composition resistance of about 150 000 ohms.

(b) Method of Cleaning Spheres.

The spheres were cleaned with ether and rubbed well with a non-fluffy rag at intervals during the course of the tests.

(c) Method of Applying Voltage, and Test Procedure.

The voltage was raised smoothly and slowly from about two-thirds of the breakdown voltage until failure occurred. Tests in which the voltage was raised slowly from a very low value indicated that there was nothing to be gained from the longer method.

The method of carrying out the calibrations followed the same general plan throughout. The cleaned spheres were subjected to a number of shots, usually of the order of 10 or 20, until reasonably consistent readings were obtained and there the calibration proper began, 20 readings being taken at intervals of about 1 minute. The gap was measured immediately at the end of each series, expanding gauges being used which permitted an accuracy of about $0 \cdot 2$ % to be obtained without difficulty. For the 200-cm. spheres it was necessary to devise a means of supporting the gauge at one end of a rod and operating it from the other, the size of the spheres making it impossible for a man of normal reach to stretch his arm into the gap from a pair of step ladders placed alongside.

(d) Selection of Results.

Each series of readings presented the same kind of problem, namely which readings should be considered as reliable and which as freaks. Bearing in mind the fact discussed in more detail later, that irradiation of all but the smallest spheres was entirely without influence on the results, the authors concluded that no high freaks

could arise from the absence of some special source of ultra-violet light, and as no other cause is known for their production it was concluded that the highest readings were the true ones and any serious departure from these values must be due to dust in the air or the settlement of occasional particles on the spheres, which would be burnt off by the spark. It was recognized, however, that slight momentary changes in the atmospheric temperature in the gap, and slight frequency-changes, might together combine to increase or decrease the observed reading by possibly 1 % as a maximum, and that therefore to select only the highest reading would be unfair.

Accordingly the mean was taken of all readings lying within a band corresponding to a maximum dispersion of 2 %. A good idea was obtained of the course of the readings by the drawing of a sequence diagram.

(e) Variables Affecting the Sparkover Values.

The relative humidity of the atmosphere was assumed to have no effect on the results within the range for which the spheres were calibrated, there being ample evidence in support of this. Similarly the temperature and pressure of the air were regarded as affecting the results only in so far as they influenced the air density, for which the usual correction was applied, the breakdown voltage being taken as directly proportional to the density within the narrow limits of its variation during the experiments.

(i) *Material of Spheres.*

The 6·25-cm. spheres were made from solid brass, turned spherical and polished in a lathe.

Tests were made with 12·5-, 25-, 50-, and 100-cm. spheres made both from spun copper and spun aluminium; the 75-cm. spheres were made of copper and the 200-cm. spheres of aluminium. No appreciable difference was observable between copper and aluminium in those cases where a direct comparison could be made.

(ii) *Effect of Irradiation with Ultra-violet light.*

The results quoted later on all but the 6·25-cm. spheres were obtained without the presence of any artificial source of ultra-violet light. The 6·25 cm. spheres, however, were found to be influenced to a slight extent at the lower spacings, and radium inserted in the high-voltage sphere was used throughout the calibration on these spheres. Some tests carried out with small brass and steel spheres, however, showed that very large errors in the breakdown voltage were liable to be obtained unless some form of irradiation was employed, the effect being greatest at about 2 kV, and a description of a few experiments on this subject is given later in the paper.

(iii) *Atmospheric Conditions.*

Most of the tests were carried out inside the laboratory, but a few series were obtained outside. Although great care was taken to make the outdoor tests on fine days with little or no wind, and if possible after a shower of rain so as to lay the dust, it was found impossible to obtain consistent results even on the rare occasions when the previously stated conditions were fulfilled, and when there were no obvious sources of pollution such as steam cranes or locomotives to windward of the spark-gap.

Numerous low freak points occurred, and the conclusion was reached that outdoor work, in an industrial area at any rate, is quite futile.

(iv) *Effect of the Use of Cascade-connected and Single Transformers.*

Apart from the effect of the voltage of the second transformer tank on the capacitance of the plate condenser, which was of course allowed for, the proximity of the large conducting surface formed by the tank wall was expected to influence the results to an extent which depended upon whether it was at zero voltage or at half the test voltage, and this was found to be so, but only when the spacing was in excess of one-half to two-thirds the sphere diameter.

The spheres up to 50 cm. diameter could be calibrated entirely with one transformer, so that the cascade connection was not necessary, but tests were made under the latter condition also as a matter of interest.

The spacings for the larger spheres at 500 kV were under one-half of the sphere diameter, and no difference could be detected as a result of a change in the transformer tank voltage.

(v) *Proximity of Neighbouring Objects.*

Except where otherwise stated, the sphere-gaps were arranged vertically with their axes 20 ft. from the nearest wall of the laboratory and 20 ft. from the wall of the tank of the second transformer. The bottom shank consisted of a steel tube 2 in. diameter and 12 ft. long screwed into the sphere. The upper sphere was supported by a steel rope $\frac{5}{16}$ in. diam. and 12 ft. long from a chain of insulators, the lead to the transformer sloping slightly upwards to the resistance and thence to the terminal bushing of the transformer.

In addition to these permanent objects in the laboratory, conductors connected to the high-voltage source were deliberately introduced at various distances from the axis of the gap, and of such dimensions and shapes that both brushing and non-brushing conditions were obtained. The effects, which were rather confusing, are described later. For the purposes of calibration such extraneous objects were not present.

(vi) *Capacity of Testing Set.*

The capacity of the testing set was increased during one series of tests by the removal of the 1·65-ohm series resistance and this had no effect, as might be expected, since the high-voltage resistance rendered the capacity immaterial so long as it was in excess of a very moderate value. It has been shown by Lusignan* that the voltage on the spheres is pulled down very sharply by the developing spark, and may on that account have to be raised appreciably before complete sparkover can take place. The extent of the fall is a function of the capacitance of the local circuit comprising the spheres and the leads on the side of the resistance remote from the transformer, and if the capacitance is very small, a high reading might be obtained. (The capacitance of

* See Bibliography, (12).

an ordinary sphere-gap and its leads is probably of the order of 50–200 $\mu\mu$F, depending upon the size of the spheres and of the gap.)

Lusignan found, however, that an additional capacitance directly across the spark-gap had no effect beyond intensifying the spark.

(6) DISCUSSION OF RESULTS AND COMPARISON WITH A.I.E.E. STANDARDS

(a) Method of Representation of Results.

The calibrations which are put forward as being applicable to spheres ranging in diameter from 6·25 to 200 cm. are shown in the form of line diagrams in Figs. 2 and 3. The proposed new standard atmospheric conditions, viz. 760 mm. Hg and 20° C. have been adopted. The method of presentation of the results is novel and perhaps requires some explanation and justification. The drawback of a calibration curve drawn on a sheet the size of a page of the *Journal* is that a distance of, say, 1 mm. represents about 0·5 % error at the upper end of the curve but about 5 % at the lower end (assuming a ratio of 10:1 for the maximum to the minimum voltage recorded). Some method was sought for, therefore, which should be more economical of space and at the same time permit greater and, if possible, more uniform accuracy. The idea of a line diagram with a linear spacing scale, proposed by Jamieson,* satisfied the condition of economy of space but still suffered from the disadvantage that the accuracy was insufficient at small spacings. After a few experiments directed towards the opening-out of the scale at the lower end, it was finally decided that a logarithmic scale of spacing offered the most satisfactory solution. The gap setting could then be read to the same percentage accuracy at all parts of the scale, and the voltage with an accuracy increasing slightly with the setting, but still substantially constant. If the diagrams had been plotted on pages the size of the *Journal* a distance of 1 mm. would have represented a change of 1·4 % in the gap length throughout, and changes of 1·5 % and 1 % in the voltage at the lower and upper ends of the scale respectively, and they could therefore have been regarded as complete calibration charts within the limits of accuracy claimed for sphere-gaps. Such diagrams are thus more accurate than 7 curves of the conventional type occupying 7 pages would have been.

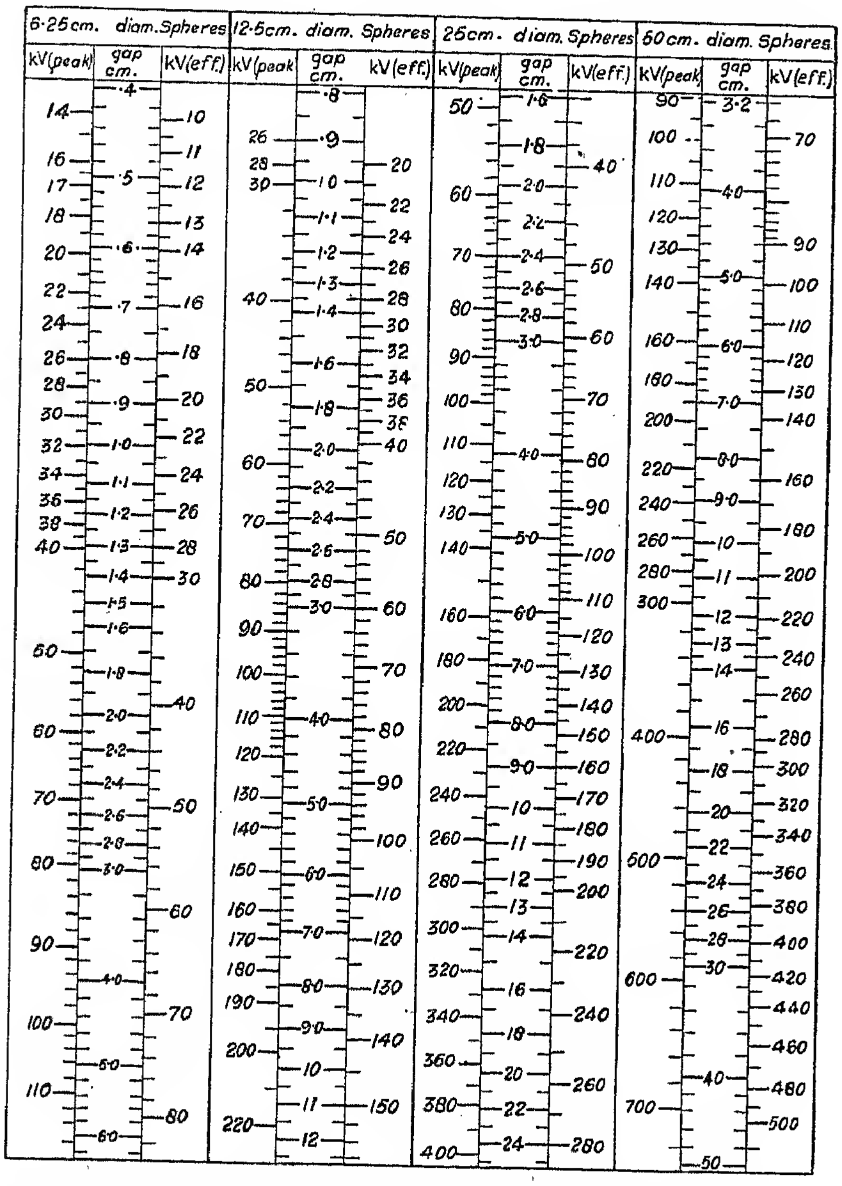

Fig. 2.—Line diagrams for the calibration of 6·25-, 12·5-, 25-, and 50-cm. spheres (one earthed) at 50 cycles. All values corrected to 760 mm. Hg and 20° C.

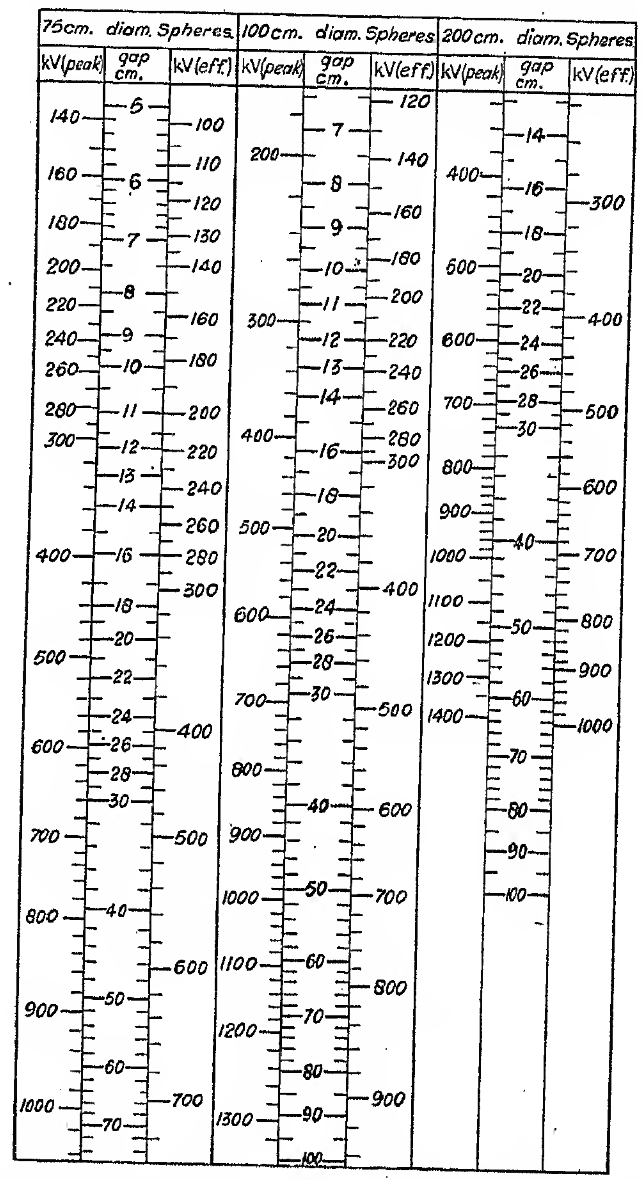

Fig. 3.—Line diagrams for the calibration of 75-, 100-, and 200-cm. spheres (one earthed) at 50 cycles. All values corrected to 760 mm. Hg and 20° C.

A slight apparent drawback of the logarithmic scale is that it cannot start at zero, but the range chosen, viz.

* See Bibliography, (13).

Plate

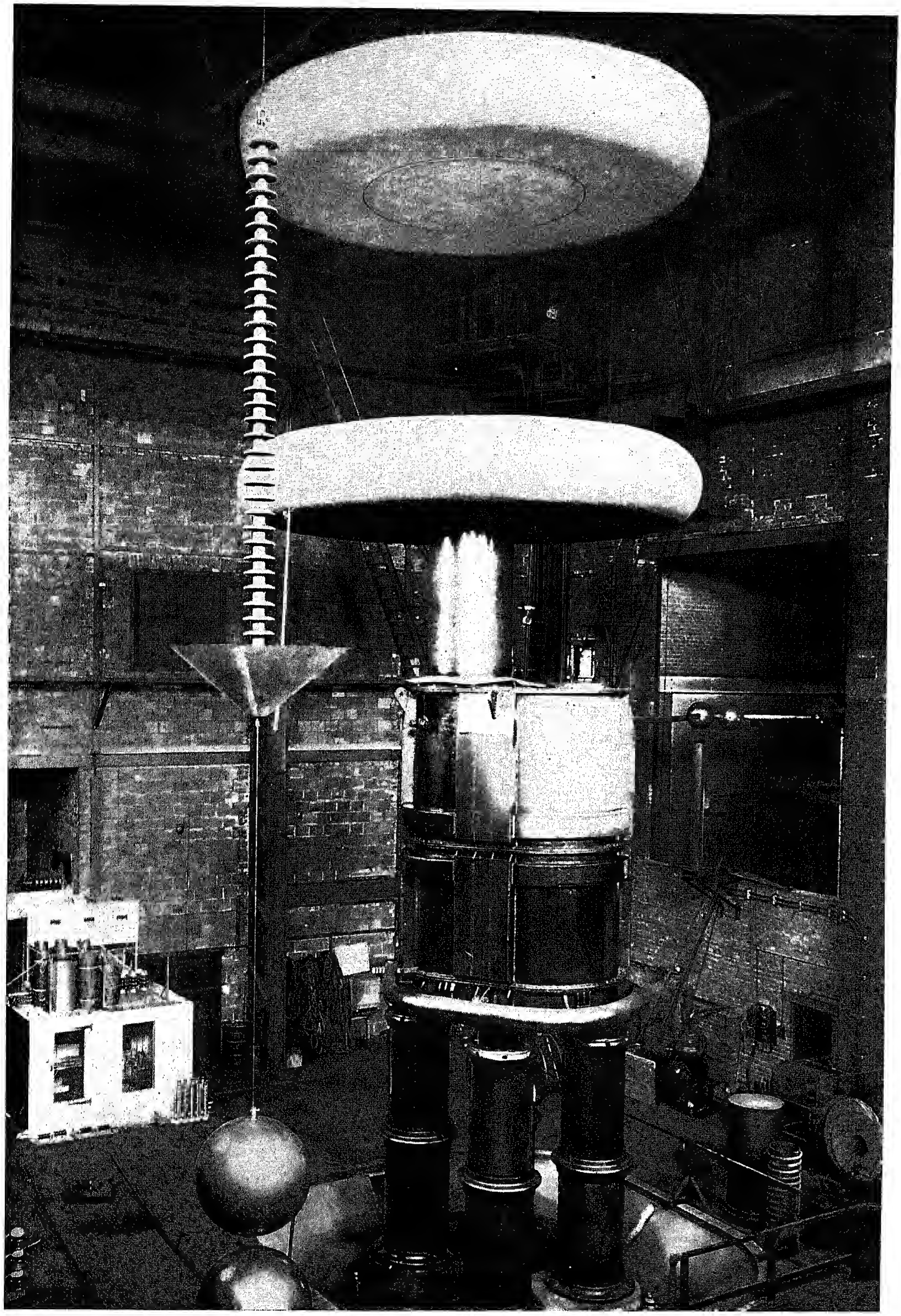

Fig. 1

from about 0·06 of a diameter to 1 diameter, represents a voltage range of about 8:1 and covers the normal working range of any particular size of sphere-gap.

If, as may happen when very large spheres are being used, it is inconvenient to change them for the purpose of an occasional measurement at a low voltage, then for spacings below 0·06 of a diameter the calibration chart of the next smaller sphere can be used without appreciable error so that the limitation can be readily circumvented.

For convenience both peak and effective (= peak/1·414) values of the breakdown voltage have been scaled in the diagrams.

proposed A.I.E.E. standards except for the largest size of spheres, while the calibrations in the present paper are about 2 % lower, except on the 12·5-cm. spheres.

The various sizes of sphere will now be considered in order.

(1) 200-*cm. Spheres.*

The only other calibration curves available for this size of sphere are those of the A.I.E.E. and of Meador.* On the average these two curves agree quite well, Meador's figures being about 0·6 to 1·2 % higher than those of the A.I.E.E., which in turn are between 1·5 and 3 % higher than the present authors' figures.

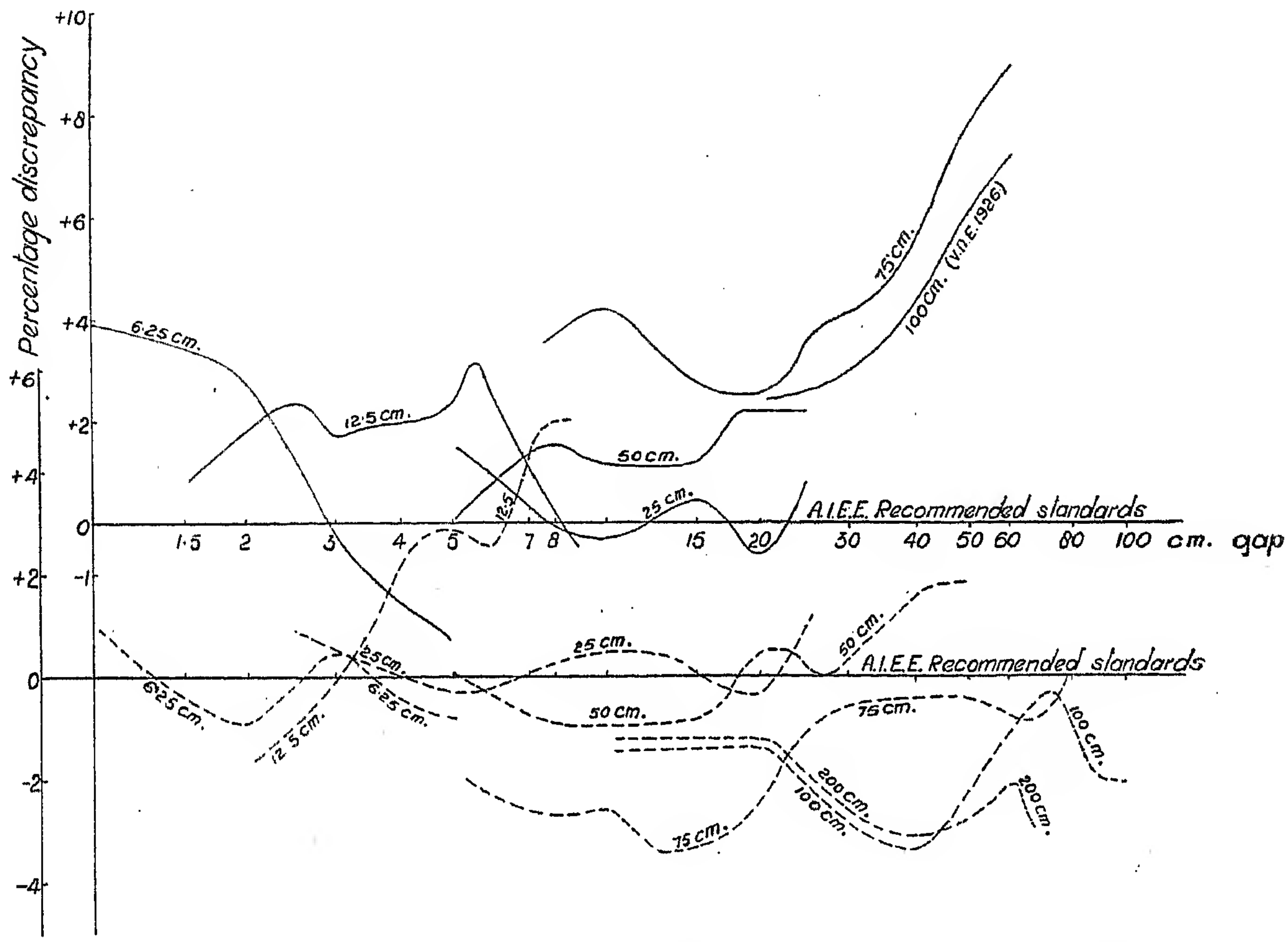

Fig. 4.—Curves showing discrepancies between B.S.I. figures of 1929, A.I.E.E. recommended standards, and present calibration.

Sphere diameters shown on curves.
B.S.I. standards (1929) ————
New calibration – – – –

(b) Comparison of Results with other Published Figures.

For the purposes of comparison it was considered sufficient to examine in detail only the figures in B.S.S. 358—1929 for spheres up to 75 cm. diameter and the V.D.E. figures of 1926 for 100-cm. spheres, these representing previously recognized standards, and to take the new A.I.E.E. figures of 1936 as representative of the latest values. With the latter as a datum, the percentage discrepancies between the various calibrations have been plotted in Fig. 4 as a function of the spacing for the different sizes of spheres. In order to accommodate the whole range of spacings from 1 to 100 cm. a logarithmic scale has been used for the abscissae.

From an examination of these curves it appears that in general the B.S.I. figures are about 2 % higher than the

Meador used a voltmeter coil and crest voltmeter for voltage measurement, and determined the wave-shape on the high-voltage side of his transformer by means of a cathode-ray oscillograph with a sphere-gap as a potential divider.

For the spacings for which a direct comparison is possible (up to $\frac{1}{3}$ of a diameter) it seems unlikely on the evidence of Kopeliovitch, Schuep, and Van Cauwenberghe† that differences in the arrangement of other objects in the various laboratories could affect the results by more than 1 %, so that there is an unexplained discrepancy of 2 % as a minimum over the range from 30 to 60 cm. [roughly 500–1 000 kV(eff.)] between the A.I.E.E. values and the authors'.

* See Bibliography, (8).

† *Ibid.*, (14).

(2) 100-*cm. Spheres.*

Meador,* the A.I.E.E., and Hueter† have published calibrations, the latter, however, up to about 500 kV(eff.) only.

Meador and the A.I.E.E. agree within less than 0·5 % and their figures are between 1·5 and 3 % higher than the authors'. Hueter's curves, unfortunately, are drawn on so small a scale that accurate reading is impossible, but it appears that his figures are about 1–2 % lower than Meador's, and in fairly close agreement with the figures put forward in this paper.

Elsner‡ has issued curves for spacings up to 100 cm. but under impulsive voltages only. As, however, according to the first draft of Recommended Sphere Gap Standards of 15th May, 1935,§ the 50-cycle and negative-impulse figures should be identical, it is perhaps worth noting that Elsner's values agree very well with Meador's (within 1 %).

(3) 75-*cm. Spheres.*

The authors' figures are about 3 % lower than those of the A.I.E.E. at small spacings from 5 to 20 cm., but thereafter the agreement is very good (within 1 %). The discrepancy with this size of sphere is thus greatest at those spacings where the presence of extraneous objects in the laboratory should have a negligible effect.

(4) 50-*cm. Spheres.*

Excellent agreement was obtained with the A.I.E.E. figures except at spacings of 40–50 cm., where the authors' figures were 2 % higher.

(5) 25-*cm. Spheres.*

Almost perfect agreement was obtained with these spheres over the whole range of spacings.

(6) 12·5-*cm. Spheres.*

Close agreement with the A.I.E.E. was obtained at spacings up to 3 cm., but thereafter the authors' figures became increasingly higher until with a spacing of 9 cm. the discrepancy was 5 %, and check calibrations confirmed the original readings.

The A.I.E.E. figures do not extend beyond a spacing of 9 cm., but in comparison with the figures of B.S.S. 358 the authors' figures are 3 % high at 12·5-cm. spacing.

A horizontal arrangement of the gap was used both for these spheres and for the 25-cm. spheres, although in the latter case comparative tests were made with a vertical arrangement as well, with only a trifling effect on the results, so that it is difficult to put forward any adequate explanation of the difference. This size of sphere seems to be peculiarly erratic in its behaviour.

(7) 6·25-*cm. Spheres.*

Very good agreement with the A.I.E.E. was obtained on the whole range. Whitehead and Castellain's calibration|| is here appreciably different from that of the A.I.E.E., being rather higher at small spacings but nearly 5 % lower at a spacing of 5 cm. At 6·25 cm. spacing it is about 4 % lower than the authors'.

* See Bibliography, (8).
† *Ibid.*, (15).
‡ *Ibid.*, (16).
§ *Ibid.*, (1).
|| *Ibid.*, (17).

(c) Effect of Brushing and Non-Brushing Conductors in Proximity of Test Gap.

It was found by Toepler* that the presence of a brushing lead connected to the same source as the high-voltage sphere is capable of increasing the sparkover voltage of a sphere-gap by a considerable amount, and he quotes a case where a wire 0·8 mm. thick stretched parallel to a 25-cm. diameter spark-gap and 60 cm. away from it increased the breakdown voltage at 50 cycles at a spacing of about 10 cm. by 10–12 %. With the same wire arranged normal to the line of the gap and at a distance of 100 cm. the increase was 2–3 %, and Toepler attributed the effect to the development of space charges in the gap.

The authors performed an experiment similar to Toepler's with the conductor normal to the gap only and using 50-cm. spheres spaced at 37·5 cm.

With a wire 0·8 mm. thick 120 cm. from the gap, the breakdown voltage was reduced by 5 %, but when the distance was increased to 180 cm. the breakdown voltage was increased by 6 % above its initial value.

When the wire was replaced by a 4-in. diameter aluminium tube the effect at 120 cm. distance was to raise the voltage by less than 1 % and at 180 cm. to raise it by 7 %.

These results are rather confusing and require further experimental investigation. The increase in breakdown voltage might be partly attributed to the weakening of the field on the high-voltage sphere due to the presence of the additional conductor, but on the other hand the increase in voltage was greater when this conductor was moved farther away from the spheres. Moreover, the thin wire, which, of course, brushed at the voltage employed [about 470 kV (eff.)] gave lower results than the large aluminium tube, so that Toepler's explanation does not seem very satisfactory, especially as mild corona on the leads has been regarded as a substitute for ultra-violet light as an ionizing agent.

(d) The Toepler Discontinuity.

This phenomenon was not deliberately examined but the final calibrations of the individual sphere-gaps were found to exhibit the effect, the small spheres at certain low settings having a slightly higher breakdown voltage than larger spheres at the same setting. As the detection of the difference in this way involved a comparison between 2 separate calibrations, nothing can be said with certainty regarding the magnitude, except that it is small.

The effect was recorded by Klemm† on small spheres up to 6·25 cm. diameter; the V.D.E. calibration tables of 1926 show it at voltages up to 33 kV(eff.), B.S.S. 358—1929 shows it at 30 kV(eff.) and Meador‡ quotes a difference of 4 % at 100 kV(eff.) between a 25-cm. and 50-cm. sphere-gap, at the same setting, but the A.I.E.E. tables contain no example at any voltage. I.E.C. publication No. 52, however, includes a calibration for 2-cm. spheres and shows increased gap settings of the 6·25-cm. spheres compared with those for the 2-cm. spheres at voltages up to 14 kV(eff.).

* See Bibliography, (18).
† *Ibid.*, (19).
‡ *Ibid.*, (8).

(e) Accuracy of Results.

Although various means of voltage measurement are confidently claimed to have accuracies of 1 part in 500 or 1 part in 1 000, and although it is considered probable that at voltages up to 500 kV(eff.) such claims may be fully justified, the difficulties associated with higher voltages are such that the authors are diffident in asserting more than that they think that they are correct within ± 1 % at 1 million volts. Other factors, however, are likely to cause appreciably greater errors in the calibration and, although they are not cumulative, their effect may be as much as ± 2 or ± 3 %.

In a large test-room such as is required for 1 million volts it has been found by actual measurement that even with all doors and windows closed the air temperature may vary by ± 1 deg. C. in and around the spark gap and by the same amount between eye-level and the gap, perhaps 8 ft. higher.

Frequency variations on a commercial testing set may account for ± ½ %, so that the possible error due to these two causes may be ± 1 %. Even in carefully controlled atmospheres, free from dust, it is found that the cumulative effect of a number of other uncontrollable variables may be to raise or lower the results by 1 %, and in addition there are the occasional breakdowns which occur at so low a voltage that they can be unhesitatingly discarded. In view of these circumstances the authors feel that the tolerance of ± 3 % quoted in the First Draft of (A.I.E.E.) Recommended Sphere-Gap Calibration Standards* (15th May, 1935) is not grossly excessive.

(7) THE POLARITY OF THE UNEARTHED SPHERE AT THE INSTANT OF BREAKDOWN

In view of its obvious bearing on the calibration of sphere-gaps with direct and impulsive voltages, the subject of the polarity of the high-voltage sphere when breakdown occurs on alternating current is one of considerable interest. Meador,* using a simple neon tube indicator, carried out a series of tests on spheres from 6·25 to 200 cm. in diameter at voltages up to about 800 kV(eff.), and these have been repeated by the authors who employed a polarity indicator consisting of 2 thyratrons which gave a permanent indication of the polarity of the discharge.*

Their results follow the same general course as Meador's but are quantitatively rather different.

Fig. 5 shows the percentage of breakdowns at the instant when the high-voltage electrode was positive, plotted as a function of the breakdown voltage, and it will be seen that the curves for the 12·5-, 25-, 50-, and 75-cm. spheres can be divided into 3 sections:—

(*a*) From zero spacing to a gap setting which is between a radius and a diameter there is a region where the polarity is rather uncertain, but with a tendency to become more negative as the spacing increases.

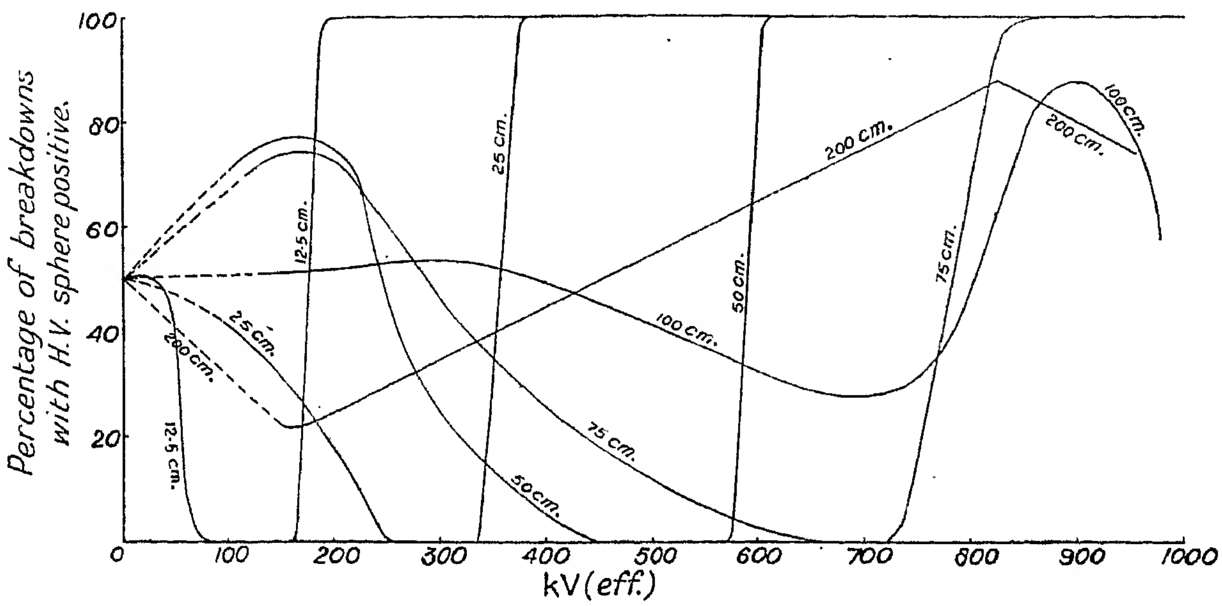

Fig. 5.—Polarity characteristics of sphere-gaps.
Sphere diameters shown on curves.

(*b*) There follows a region where all the breakdowns occur on the negative half-cycle.

(*c*) At a spacing between about 1·5 and 2 diameters the number of positive breakdowns rises very sharply indeed and for any larger spacings all the breakdowns are positive.

The sudden nature of the transition is very clearly shown when breakdown voltages are used as abscissae. Meador plots spacings, and the effect is consequently masked in his diagrams on account of the flat nature of the breakdown-voltage/spacing curve above a diameter.

It should be noted that in Fig. 5 the individual points have been omitted. The results on the 12·5-, 25-, and 50-cm. spheres were very consistent and the curves shown are drawn through the experimentally determined points, except for very small spacings.

The figures for the 75-cm. spheres were not so regular, and for the 100-cm. spheres it was difficult to draw a curve at all. The points for the 200-cm. spheres on the other hand, within the limited range over which they could be tested, were very regular.

Even at a spacing of 120 cm. it was not possible to obtain a very definite bias in the polarity of the breakdown voltage of the 100-cm. spheres, and this observation

* See Bibliography, (8).

* See Appendix.

is confirmed up to a point by the N.P.L.,* who could not detect any polarity effect on 100-cm. spheres under impulsive voltages at a spacing equal to the radius, whereas the First Draft of (A.I.E.E.) Recommended Sphere-Gap Standards (15th May, 1935) showed that at this spacing the positive breakdown value should be 4 % higher than the negative.

The range over which it was possible to test the 200-cm. spheres was so narrow (up to 65 cm. only) that it revealed no pronounced polarity effect.

It should be added that in Fig. 5 all the curves have been made to go through the 50 % ordinate at zero voltage. This is purely conjectural but is based on the fact that with a very small gap the field is perfectly uniform and consequently it ought to be a matter of pure chance whether the high-voltage sphere happens to be positive or negative relative to the earthed sphere at the instant of breakdown. The deciding factor in such a case is the relative condition of the sphere surfaces and this was shown by the following experiment. A 25-cm. sphere-gap was erected horizontally with both spheres arranged perfectly symmetrically with respect to each other, to the sphere shanks, and to earth, with a gap of 0·9 cm., and under these conditions 28 out of 50 successive breakdowns occurred with the high-voltage sphere positive. The high-voltage and earth leads were then interchanged, and it was then found that 28 out of 50 successive breakdowns occurred with the high-voltage sphere negative. Then the two spheres were interchanged on their shanks, the connections to the shanks remaining as for the previous test, and now 28 out of 50 breakdowns were positive again. Finally the spheres were untouched but the connections were reversed again. In this case 32 out of 50 breakdowns were negative. The consistency of the proportion of breakdowns of one sign to those of the other (except in the last case) is rather remarkable and confirms that at small spacings the polarity at breakdown is dependent solely on the relative condition of the spheres. If the direction of breakdown is influenced not by more or less permanent irregularities on the spheres but by dust particles, etc., it will be evident that widely differing results will be obtained from day to day, or even from hour to hour, when the gap is relatively small, and this is found to be the case.

At larger spacings within the range where all the breakdowns occur on the negative half-cycle it is possible to reverse their polarity if a very small lump of plasticine is placed on the high-voltage sphere. Another effect of the plasticine is to reduce the actual breakdown voltage enormously. Thus a conical piece of this material about ⅛ in. high placed on the earthed 200-cm. sphere, in a gap which had been breaking down at 840 kV(eff.) caused the breakdown voltage to fall to about 680 kV(eff.) and when the height was increased to about ⅜ in. the voltage was only 360 kV(eff.).

McMillan and Starr† preceded Meador in their determinations of the polarity characteristics of small spheres of 2·54, 6·25, and 25 cm. diameter, and obtained somewhat similar results.

A feature which was noticed during the polarity tests was that the sound of the breakdown was so distinctive that from it could be deduced with complete certainty (except at small spacings and in a few special cases) the polarity of the discharge, which was confirmed by the polarity indicator and by oscillographic records. Negative breakdowns gave a sharp crack like that of a whip, while positive breakdowns resulted in a buzzing noise. The only published reference which the authors have been able to discover on this subject is a casual statement by Claussnitzer,* who was engaged in comparing two spark gaps directly and stated that breakdowns were only regarded as trustworthy if they occurred with a sharp crack (" Knall "), but he does not explain why he considered the sound significant.

* See Bibliography, (2).

† *Ibid.*, (20).

One of the authors recalls having heard it stated at a meeting some years ago that, in a series of readings on the same gap, low values were associated with one kind of noise and high values with another kind of noise, but the reference has not been traced, and no indication has been found that readings of one polarity are consistently higher than those of the other.†

It was observed, however, that on rare occasions the first few shots of a series were rather low and resulted in a buzzing noise and an indication of positive polarity, while the remaining shots were higher and had the characteristic sound and gave the indication of a negative breakdown.

In a particular case of 50-cm. spheres spaced 45 cm. apart the first 6 breakdowns (all positive) had an average value of 490 kV(eff.) and the remainder of the series (all negative) had an average value of 500 kV(eff.).

On another occasion when 75-cm. spheres, spaced 27·3 cm. apart, were being tested, a long series of consistent negative breakdowns was obtained at a voltage of 431 kV(eff.), but this was broken by two successive failures at 422 kV(eff.), also of negative sign. The sound of these two breakdowns, however, was unmistakably soft and characteristic of a positive failure. It is suggested as an explanation of this instance of disagreement between the polarity indicator and the sound of the breakdown that a foreign body of some kind had fallen on to the lower sphere and produced what was virtually a point-sphere arrangement.

A few power-frequency spark discharges were examined with a rotating camera giving a resolution of 24 microseconds per millimetre of trace, the 25-cm. spheres being used for this purpose. Gaps of one and three diameters were employed. With a spacing of 1 diameter breakdown began at the insulated sphere with the formation of a leader-stroke of the kind now associated with the lightning flash. From its appearance it could be identified as starting from a negatively charged sphere, and it had the same characteristics as the leader-stroke of an impulse spark of negative sign. When this spark had developed across a part of the gap another leader started from the earthed sphere and the two sparks met somewhere near the middle of the gap, with the main spark following.

At a spacing of 3 diameters, on the other hand, the breakdown started at the insulated sphere with the formation of a leader-stroke of the kind which precedes

* See Bibliography, (21).

† Since the paper was first submitted it has been discovered that the remark in question was made by Mr. G. H. Halton, who in a recent communication to the authors stated that he found abnormally low values of breakdown to be associated with " a rather hollow sound," as compared with the " sharp crack " which occurs with normal values, and this observation is interesting as showing the probable reason why Claussnitzer only admitted values associated with a sharp crack.

a positive impulse sparkover. These results indicate that breakdown had occurred on the positive half-cycle at a spacing of 3 diameters, and on the negative half-cycle at a spacing of 1 diameter, but in the latter case it was accompanied by breakdown from the earthed sphere also.

As foreshadowed by McMillan and Starr,* sphere-gaps exhibit a marked polarity effect under impulsive voltages, substantially as might be expected from the trend of the polarity/spacing curves obtained at 50 cycles.

The authors investigated this matter and found that with 25-cm. spheres the positive and negative impulse curves for a 1/300-microsecond wave were coincident at small spacings, but the negative curve soon began to fall markedly below the positive, and the two curves crossed again at a voltage of about 490 kV(peak) and a spacing of about 2 diameters. Thereafter the negative curve bent sharply upwards above the positive curve.

Reference to Fig. 5 will show that the voltage for 50 % of positive breakdowns at 50 cycles at the point of rapid transition is about 355 kV(eff.) or 503 kV(peak), so that the ranges over which the breakdown is mainly on the positive or mainly on the negative half-cycle agree almost exactly with what might be expected from the results of the impulse-voltage tests, and are also confirmed qualitatively by the photographic records just mentioned.

(8) EFFECT OF ULTRA-VIOLET LIGHT ON THE CALIBRATION OF SPHERE-GAPS

It does not appear to be generally appreciated that a sphere-gap calibration at small spacings may be very seriously in error (up to 80 %) unless some means are adopted for irradiating the gap.

It is true that in the V.D.E. rules of 1926 irradiation is recommended for voltages below 30 kV(eff.) in order to eliminate time lag: but B.S.S. 358–1929 is silent on the subject and Whitehead and Castellain† found that an arc lamp only affected the results by ½–2 % between 10 and 60 kV(eff.) when 6·25-cm. spheres were used. It is interesting, in the light of the tests described below, to note that the percentage decrease in breakdown voltage decreased slightly as the voltage increased, being nearly 2 % for a spacing of 4 mm. [10 kV(eff.)] and about 0·5 % for a spacing of 34 mm. [60 kV(eff.), approx.] Hueter,‡ using steep-fronted impulses of unstated magnitude, looked for, but failed to find, any effect on spheres of 4, 5, and 10 cm. diameter. On the other hand in 1923 Klemm,§ using a sphere-plate arrangement with direct current, the sphere being 4 cm. in diameter, at distances of 0·005–0·04 cm. from the plate, reported that in the absence of a mercury-vapour lamp the means of a series of readings were from 5 to 30 % too high, and also very erratic; the maximum error in any one reading being 60 %. The voltage at which this error occurred was about 2 kV (d.c.). Van Cauwenberghe and Marchal‖ also made tests at 50 cycles (a.c.) repeating tests carried out by Rogowski,¶ who had found that radium as a source of ultra-violet rays was much inferior to a mercury-vapour lamp. Van Cauwenberghe had the ingenious idea of drilling a hole in the back of one of the electrodes and continuing it through the electrode until only a thin wall of metal remained (about 2 mm.), and placing the radium at the bottom of the hole. This method had the double advantage of not introducing the slightest distortion into the field and of ensuring that the radiation was precisely where it was required, the operation of the inverse-square law making 1 mg. in the sphere as effective as 2·5 g. 10 cm. away. Van Cauwenberghe found that when using a 5-cm. sphere with a gap of 3 mm., corresponding to about 8 kV(eff.), he was able to obtain extremely consistent results with even 0·5 mg. of radium, and the substitution of 10 mg. had a negligible effect. With an open arc lamp 24 cm. away the results were almost as good, but slightly higher and slightly less regular, while in the absence of any irradiation at all the mean breakdown value was increased by 11 % with a maximum reading in the series over 30 % too high.

* See Bibliography, (20). † *Ibid.*, (17). ‡ *Ibid.*, (15). § *Ibid.*, (19). ‖ *Ibid.*, (22). ¶ *Ibid.*, (23).

A number of investigators* have reported that the use of radium greatly reduces the time-lag of breakdown of sphere-gaps under impulsive voltages, but the maximum time-lags recorded were only of the order of 100 microseconds, while a sinusoidal voltage at 50 cycles is within 1 % of its maximum value for 900 microseconds, so that some other explanation is needed for greater overvoltages than about 1 %.

The authors have carried out a short investigation at 50 cycles with 13-mm., 16-mm., and 62·5-mm. spheres in order to determine to what extent the length of the gap and the site of the tests affected the error due to the absence of ultra-violet light, as these two variables do not appear to have been previously examined. It was found that errors up to 80 % might be met with in unfavourable circumstances, that the effect was still appreciable at 24 kV(eff.), that it varied from day to day and from site to site, that the standard deviation of a series of measurements on 13-mm. spheres bore a roughly linear relation to the mean percentage error, and that after passing through a maximum at about 2 kV(eff.) both error and deviation diminished in a rather uncertain manner as the gap was increased, until at 18 kV(eff.) the error was 6 % at one site and 2 % at another, the corresponding standard deviations being 5 % and 1·5 %.

The 16-mm. sphere-gap was tested with an arc lamp as the radiating source, while the other 2 gaps were calibrated with radium capsules in the unearthed sphere. A small hole was drilled concentric with the shank and reaching to within 1 mm. of the surface of the sphere nearest to the gap, and the radium was placed at the bottom of the hole in the manner suggested by Van Cauwenberghe. Tests were then made in air as follows:

(*a*) On the 13-mm. (brass) sphere-gap with and without 0·5 mg. radium.

(*b*) On the 62·5-mm. (brass) sphere-gap with and without 0·5 mg. radium.

(*c*) On the 16-mm. (steel) sphere-gap with and without an arc lamp shining on to the gap and placed about 10 in. away from it.

Test (*a*) was made at a works in the Manchester district, which for convenience is called site A, and also at a works in the London district, designated site B.

* See Bibliography, (24), (25), (26).

Test (*b*) was made at site A only.

Test (*c*) was made at site A and also at a works some miles away, which will be described as site C.

In general 10 tests were made under each condition of gap setting, radiating source, and site.

of the error curve with increasing gap setting was shown in Whitehead and Castellain's paper.)* There is a maximum point on both curves at a spacing of 0·020–0·030 in., with a marked reduction in the irregularities on either side.

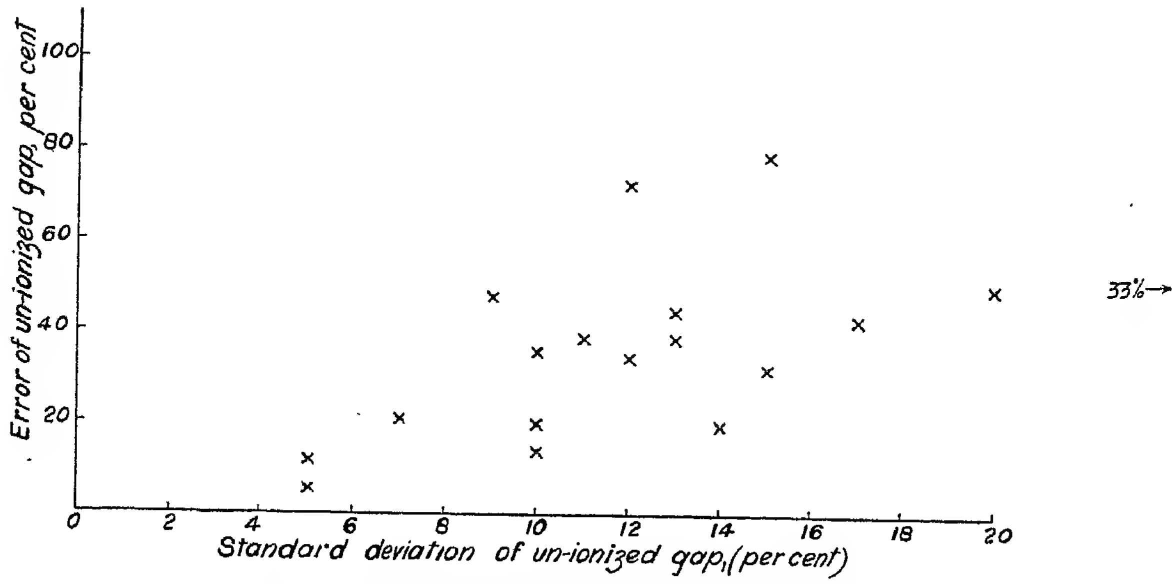

Fig. 6.—Relationship between standard deviation and percentage error of un-ionized gap at site "A."
13-mm. diameter brass spheres.

Fig. 6 shows the relationship between the standard deviation and the percentage error of an un-irradiated gap at site A. The correlation between the two quantities is not very good but it is evident that there is a tendency for a high standard deviation to be accompanied by a large error in the results. From this it might be concluded that consistency is synonymous with accuracy—a statement which is usually, but not invariably, borne out by the facts.

Fig. 7 shows the downward trend of the error and standard deviation for 13-mm. brass spheres at site A as the gap setting is increased. (This downward trend

Some of these tests were repeated with 0·2 mg. of radium instead of 0·5 mg., and rather higher values were obtained at small spacings, but from 2 kV onwards the effect was negligible.

Mme. Vereecken† found somewhat similar results under impulsive voltages, slightly greater consistency and slightly lower values being obtained with the larger quantity of radium but at a voltage of about 6 kV(peak).

At site B the standard deviation and the error for un-irradiated 13-mm. spheres were on the average rather lower than at site A. The maximum error in the mean

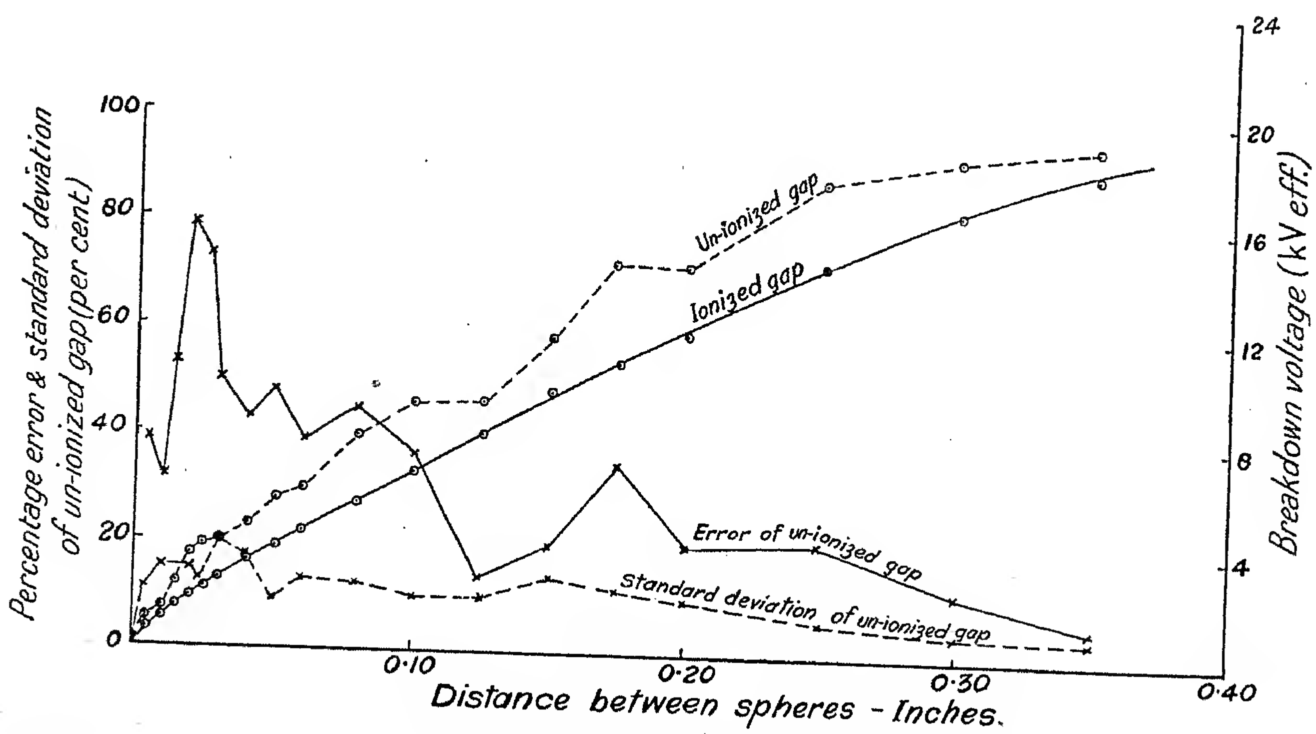

Fig. 7.—13-mm. sphere-gap with 0·5 mg. radium at site "A." Conditions: 760 mm. Hg and 25° C.

* See Bibliography, (17).

† *Ibid.*, (26).

of any series of readings was 38 % against 79 % at site A, and the maximum standard deviation was 16 % against 33 %.

The results on the 16-mm. steel sphere-gap were unexpected. Errors up to 84 % and standard deviations up to 16 % were obtained at site A when no source of radiation was used, but a carbon-arc lamp 10 in. away reduced the deviation to 3 % as a maximum. When the test was repeated at site C, however, the arc had no effect whatever on the magnitude of the results, and the standard deviation was very low both with and without the arc. The weather on this occasion was very wet and misty, and it was thought that the high humidity might be the cause of the anomaly; but other tests did not confirm this idea. A day was selected when the air at site A was unusually humid, and a test was made with the 13-mm. spheres. The error was 23 % and the

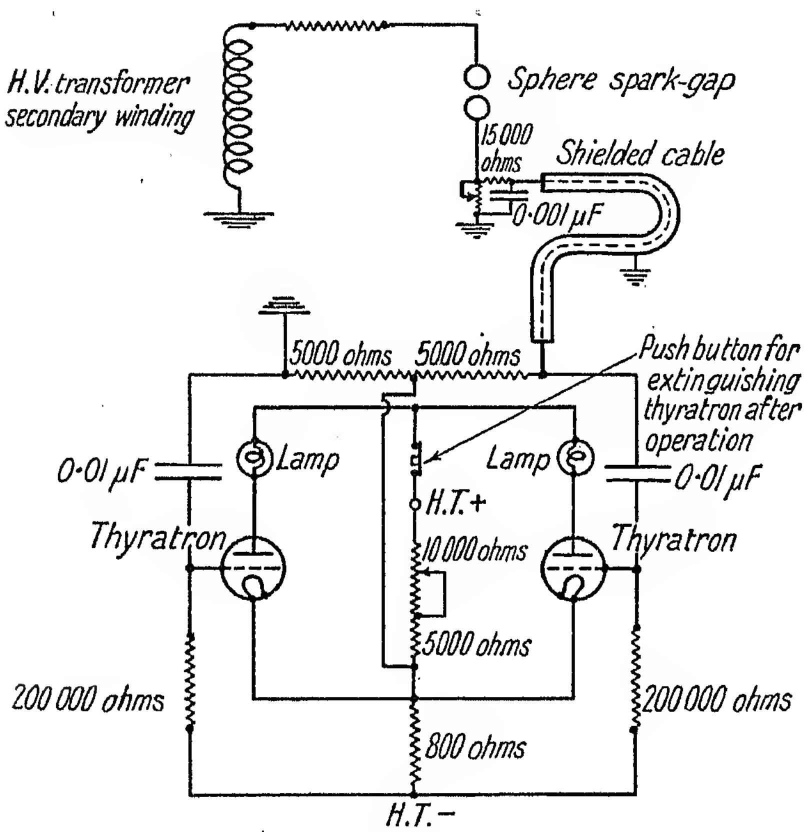

Fig. 8.—Schematic diagram of polarity indicator circuit.

standard deviation 11 %. On another damp day the figures were 7 % and 3 %, so that high humidity does not in itself give rise to accurate and consistent results.

The 62·5-mm. spheres also gave rather strange results. On a test at site A on the first floor of a building, the standard deviation without radium was 12 % and the error 40 %, at a spacing of 0·05 cm. [= 1·8 kV(eff.), approx.], the corresponding figures at a spacing of 1 cm. [= 23 kV(eff.), approx.] being 3 % and 7 % respectively. When the test was repeated on the ground floor of the same building the figures at the larger spacing were 1·5 and 1 % respectively, and at still larger spacings (up to 9 cm.) the error and the deviation were about 1 % or less. The difference in results on two floors of the same building is curious, and Hueter's observations* are of interest in this connection. As previously stated, this author could not detect any effect due to the presence of a mercury-vapour lamp, and he remarks that his test room had no cellars, so that the strongly ionized air on the ground (Bodenluft) had ready access.

Tests with 6 arc lamps placed 20 ft. from a 100-cm. sphere gap at a spacing of 10 cm. had no effect on the breakdown voltage, and when the spacing was increased to 75 cm. an increase of $\frac{1}{2}$ % was obtained. The difference is so slight, however, that it is regarded as accidental, and the conclusion is held that no errors will arise in the use of such large spheres as a result of the absence of any special source of ultra-violet light.

* See Bibliography, (15).

(9) ACKNOWLEDGMENTS

Except where otherwise stated, the experimental work described in this paper was carried out in the High Voltage Laboratory of the Metropolitan-Vickers Electrical Co., Ltd., and the authors are indebted to Dr. A. P. M. Fleming, C.B.E., M.Sc., Director and Manager of the Research and Education Departments, for his continuous encouragement and for his permission to publish their results. Messrs. G. J. Scoles, B.Sc.(Eng.), and J. A. Nott, B.Sc.(Eng.), were largely responsible for making the polarity indicator work satisfactorily.

Mr. J. B. Mitford, a former member of the Research Department staff, co-operated in the early stages of the work, especially in connection with voltage measurement, while the suggestions and criticisms of Dr. T. E. Allibone and other colleagues in the High Voltage Laboratory were of great assistance.

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APPENDIX

Polarity Indicator

The polarity indicator referred to in Section (7) is shown diagrammatically in Fig. 8. It consists of two thermionic grid-controlled discharge devices (" thyratrons ") so connected that when either of them receives a positive impulse this thyratron is energized, while the other is simultaneously " locked out " by the imposition of a high negative potential on its grid and a fall in its anode voltage. A negative impulse on one grid is accompanied by a positive impulse on the other, so that according to its sign an impulse affects either one or other of the thyratrons.

The instrument was mounted on the control desk and connected to the spark-gap by means of a shielded cable. The first quarter-cycle of the power-frequency current following the breakdown of the test gap provided the necessary tripping voltage.

[The discussion on this paper will be found on page 669.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 7TH JANUARY, 1938, ON THE PAPERS BY MESSRS. DAVIS AND BOWDLER (SEE PAGE 645) AND MESSRS. EDWARDS AND SMEE (SEE PAGE 655)

Prof. W. M. Thornton: It is over 200 years since spheres were first used on electrostatic machines as sparking terminals, and, one may infer, since the length of the gap was first used as a rough measure of the sparking potential. Within the last 10 years the accuracy of this type of measurement has been increased until, as in the present paper, a dispersion of 2 % is obtainable from the mean value, a figure that is still too large to be called accurate. In Messrs. Edwards and Smee's paper it is stated that "Purely theoretical calculations of the breakdown voltage of an air-gap between electrodes of a given shape are impossible." It is true that the sparking distance cannot be calculated for sphere-gaps, but it can for parallel-plate electrodes with rounded edges, where the dispersion of successive sparking voltages from the mean is a fraction of 1 %. Dr. Stephenson made a long series of spark-gap measurements some years ago in my laboratory, the dispersion being within 0·1 % for electrodes with parallel surfaces. In no case does sparkover between spheres take place in a uniform field. Does this explain what the authors call "apparent changes in the electric strength of air with the curvature of the electrodes," a most unlikely physical variation? It is only at very small spacings that the results agree for spheres of different diameters: the voltage that a given length of gap will carry increases rapidly with the diameters of the sphere electrodes. When, on the other hand, the electrodes have parallel surfaces, with rounded edges, the voltage that a given length of gap will carry is the same for all diameters of electrodes, within the working range. Beyond a certain (large) separation sparks pass from the edges of the electrodes, but the working range is clearly defined in each case. Within this range sparkover always occurs in the uniform part of the field. The visible effects of sparkover on the state of the surfaces are not so marked on parallel gaps as on spheres, where the sparking region is much more concentrated. The relative spreads of the sparking areas are between 500 and 1 000 to 1 in favour of parallel-plate electrodes. As the potential is raised, corona forms on the supports, and as the sphere-gap is widened electrons from this corona are caught by the field between the spheres and attracted to the positive pole, forming a space charge as they approach it. This may well give rise to leader sparks at the positive pole and be the reason for the sparks that start at the positive pole when the spacing is wide. We have been engaged for some years in a comparison of various methods of measuring high potential-differences, and the evidence that we have collected shows that parallel-plate electrodes with suitably-rounded edges provide the opportunity for practical high-voltage measurements with at least 10 times the consistency of sphere-gap measurements.

With regard to impulse sparkover, the random ionization of the air of a room (by which the sparkover path is determined) is by no means uniform. When the electrodes are spheres, the choice of path is limited to the small region of air between their nearest surfaces, in and out of which stray ions are moving with great rapidity. One would therefore have expected more variation due to irradiation, by an adjoining spark as in Hertz's case, or by ultra-violet light in general. This is mentioned in Edwards and Smee's paper but not by Davis and Bowdler. In impulse work, irradiation of sphere-gaps increases the consistency of the results and reduces the impulse ratio by providing more ions to start the process of ionization by collision. Have the authors considered this point?

In a laboratory of minimum dimensions we have entirely got rid of corona up to 250 kV by observing the spots where it occurred and rounding them off with Henley's plastic compound or plasticine. We are at present engaged in calibrating three sets of parallel-plate electrodes, first for 50-cycle flashover and then, if possible, for impulse flashover.

Dr. S. Whitehead: It is 9–10 years since the E.R.A. first emphasized the need for extending the then existing sphere-gap calibration up to 1 million volts. At that time, facilities for work above 100 kV were rare in this country and were occupied with more urgent work; but the organizations with the necessary facilities promised to attack the problem as soon as circumstances permitted. The present authors' contribution to that work is well worth waiting for and need not fear comparison with the research on the same lines which has been carried out in America and Germany.

Before 1926, the American (1916) figures were usually employed. In 1926, 2-cm. spheres were added to replace needle-gaps for lower voltages, which were unreliable on account of humidity effects. A little later, 75-cm. spheres were added and a number of changes were made in the earlier tables as a result of new work in various countries; the net result was the adoption by the I.E.C. of values up to 820 kV (effective) which are substantially the same as those in B.S.S. No. 358—1929. As a result of a suggestion made by the late Mr. A. R. Everest in 1926 a special study of what is now known as the Toepler discontinuity was made in this and a few other countries, which showed the probable crossing of the curves for 2-cm. and 6·25-cm. spheres as compared with larger spheres. The American 1916 figures also showed the effect for 6·25-cm. spheres at 30 kV, but the magnitude of this is now known to be very small. About 1934, the I.E.C. formed a Sphere-Gap Panel to revise their calibrations. Up to this time, the V.D.E. in Germany had taken the attitude that calibrations should be calculated from

Peek's formula, for the sake of theoretical uniformity. The I.E.C., the U.S.A., and Great Britain, on the other hand, adopted the principle of experimental calibrations adapted to conditions defined as carefully as knowledge permitted. Germany has since agreed with this point of view, and at Scheveningen in 1936 it was considered that the recent German work agreed fairly well with the new American figures for 50-cm., 75-cm., and 100-cm. spheres, provided the spacing was limited to 75 % of the diameter, while the earlier figures for smaller spheres were regarded as satisfactory, subject to the same limitation of spacing. A number of minor changes were made to improve the consistency and fit them with mean values, and this resulted in I.E.C. Publication No. 52.

The E.R.A. are now preparing some tables to replace B.S.S. No. 358—1929. The limitation of the spacing to 75 % of the diameter has so far been maintained, and for the case of one sphere earthed the figures of I.E.C. Publication No. 52 have been taken as a basis. The tables will, however, probably include 150-cm. and 200-cm. spheres and also tables for the case of both spheres insulated, and an attempt has been made to take account of some recent work.

As has already been mentioned by Prof. Thornton, the difference in the calibrations for spheres of different sizes demands a check on the consistency between different sizes. This is conveniently achieved in making use of the relation which I put forward some years ago, namely

$$\epsilon = \epsilon_0 + a^{-\frac{1}{2}} f\left(\frac{s}{a}\right)$$

where ϵ is the field strength at the sphere surface for sparkover, a is the sphere radius, and s the spacing. This gives a series of straight lines when ϵ is plotted against $a^{-\frac{1}{2}}$. These lines are shown for the proposed E.R.A. calibrations in Fig. A, and are compared with the points taken from the calibrations of the present authors.

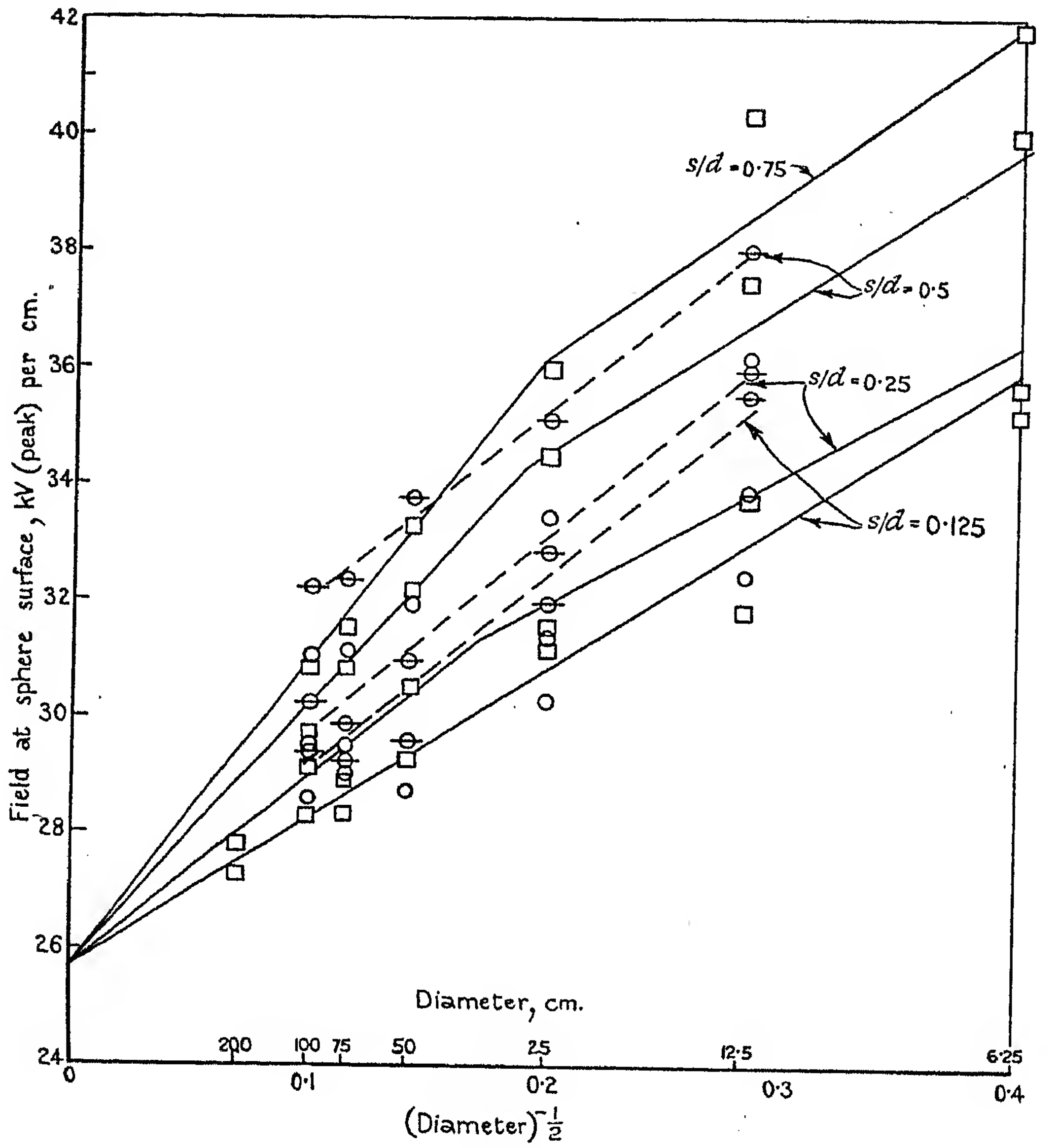

Fig. A

Proposed standards.
50 cycles per sec. } (Davis and Bowdler).
Negative impulse } (Davis and Bowdler).
50 cycles per sec. (Edwards and Smee).

It is noted that for larger values of s/a the lines are in two parts having different slopes, the intersection being apparently related to the Toepler discontinuity. The formula may also be expressed as:—

$$\epsilon = \epsilon_0 + s^{-\frac{1}{2}} \phi\left(\frac{s}{a}\right)$$

As a becomes very great, $\phi(s/a)$ must become constant since the field is then independent of sphere diameter; thus, for a uniform field,

$$\epsilon = \epsilon_0 + (s^{-\frac{1}{2}} \times \text{const.})$$

which is the Toepler–Stephenson formula for a uniform field. The value of ϵ_0 in Fig. A is approximately 18 kV (eff.) at 20° C. and 760 mm., which is in reasonable agreement with Prof. Thornton's value, bearing in mind the uncertainty of the extrapolation. It may also be noted that the method of Fig. A condenses all the readings on large spheres into a very small area corresponding to a range not greatly exceeding 10 % of the absolute values.

The power-frequency figures given by the authors are in good agreement with the values proposed by the E.R.A. With the exception of one or two isolated points, the results of Messrs. Edwards and Smee agree within about 2 %, except for 100-cm. spheres, where they are increasingly lower than the E.R.A. results as the spacing increases; but the results of Messrs. Davis and Bowdler are increasingly higher for these spheres, the mean curve between those two sets of results agreeing very well with the E.R.A. draft values. For spheres of other sizes the results of Messrs. Davis and Bowdler show rather an irregular and greater divergence than those of Messrs. Edwards and Smee.

For insulated spheres a set of lines similar to those in Fig. A may be deduced therefrom, bearing in mind that the calibrations for earthed and insulated spheres are the same for small values of s/a, while the points for smaller spheres are known from existing fairly well-established investigations. In this way sufficient points on the lines may be established to permit their completion, and the possible error is rather less since the lines slope less for insulated than for earthed spheres. The calibrations so deduced agree with the recent results of Hueter, as far as his method of presentation permits.

The E.R.A. have also prepared draft line diagrams similar to those given by Messrs. Edwards and Smee, this form being very convenient as an adjunct to tables in published specifications.

By the American workers, and also at the recent I.E.C. meeting, the a.c. and negative-impulse values were taken as the same up to a spacing equal to the radius. Though the results of Messrs. Davis and Bowdler suggest that this assumption may be accurate within 5 %, yet the impulse values differ consistently and may be expected to show very large discrepancies with small spheres. Again, if, as the authors conclude, the sphere-gap has an impulse ratio to impulses of either sign, its effective time-lag must be longer than has been hitherto supposed. This is not altogether consistent with the authors' experiments with different wave-shapes. A further investigation of this matter seems desirable, and it might be interesting to include small spheres.

Messrs. Edwards and Smee refer to the low values which Mr. Castellain and I found for large spacings with 6·25-cm. spheres. At the time we mentioned our difficulty of repeating calibrations many months apart in this particular case, and gave reasons for ascribing it to temperature-changes. I have since confirmed that the reason for much of this discrepancy was a difference in temperature between the sphere and the air, which may easily arise with solid spheres in a large room owing to different conditions of thermal equilibrium applying to the metal and the air.

Messrs. Edwards and Smee also agree with our observation as to the lack of effect of humidity, but I should like to ask how far such an effect is absent with impulse voltages. The intrinsic calibration accuracy for alternating current can now be put at a lower figure than 3 %, but it is clear that a number of readings must be taken to reduce the mean deviation.

Messrs. Edwards and Smee appear to concur with the view, which I and others have expressed, that, owing to the occurrence of occasional anomalous shots, the sphere-gap should not be used without some means of recognizing the occurrence of such strays. Would they recommend for standard use the method of selection of readings employed by them, when the sphere-gap is used to calibrate an auxiliary voltmeter, which is probably its most frequent use? I should also like to ask the authors' opinion as to the prospects of devices such as the caged gap and the sphere-gap with guard rings.

Dr. T. E. Allibone: In Fig. 4 of their paper Messrs. Edwards and Smee report rather lower values of sparkover than are given by the American I.E.E. for the larger sizes of spheres; and for voltages up to 420 kV Messrs. Davis and Bowdler report even lower values. I hope that when Dr. Whitehead on behalf of the E.R.A. takes note of the recommendations which will be put before the I.E.C. next summer he will bear in mind the work of these two groups of investigators, together with that of Hueter in Germany. The I.E.C. ought not to adopt the A.I.E.E. proposals exactly as they stand without taking into account the three new contributions.

Messrs. Davis and Bowdler have to extrapolate above about 420 kV (eff.), but this is quite a justifiable procedure if they themselves are entirely satisfied with it. I would merely suggest that a few more details of the manner and possible error of extrapolation would be welcome. I also think that their paper would be enhanced in value if they would give a few details with regard to the dispersion of the results of power-frequency measurements and also of impulse-voltage measurements. From their oscillograms can they give statistics of the time-to-sparkover under impulse voltages for different spheres and for different spacings?

In connection with polarity of sparkover on power-frequency voltages the results obtained by both groups of authors differ from those of Meador, and McMillan and Starr. Neither of the present papers gives the number of observations which were made, whether with the cathode-ray oscillograph or with the polarity indicator. Was the number of observations made at any one spacing sufficient to give a correct impression of the percentage distribution of the spark between positive and negative polarity? If so, I suggest that the cause of the discrepancy between the results obtained by the four independent groups of workers is that there is not much difference between the true breakdown voltages on positive and on negative constant potential at any one spacing, and that therefore the chance of breakdown occurring on a given polarity of the a.c. wave is affected by small influences such as the field in which the spheres are situated and the length and diameter of the shanks.

It might be profitable to investigate this subject with an a.c. voltage wave biased by a small percentage in one direction or the other, e.g. by passing direct current through the transformer primary, so that the secondary

voltage is made higher on the positive half-cycle than on the negative half-cycle, or vice versa. This seems to me to be the only way of observing the true breakdown voltage throughout the whole range of either the positive or the negative half-cycle, as it is unlikely that in the near future we shall have constant d.c. voltages available to such a high value as 1·4 million volts.

Regarding the differences between the sparkover values of spheres for positive and negative impulse voltages and for power-frequency voltages, I am prepared to agree that the tests carried out by Messrs. Davis and Bowdler show that these differences occur, but I submit that careful analysis of the test conditions shows why these differences are present. I believe that under truly comparable conditions the spacings at which the positive and negative impulse flashover values start to diverge will be the same as those at which all the power-frequency sparks start to occur mainly on the negative half-cycle, for I cannot understand why a different mechanism should exist for spark formation on impulse voltage from that which exists for 50-cycle voltage, for gaps which do not form corona before sparkover. If we plot the voltage of breakdown for any gap against the time to sparkover, we find a remarkable difference between the impulse-sparkover voltage/time-to-sparkover characteristics of the positive spark and of the negative spark: briefly, the positive sparkover-voltage/time characteristic slopes rather rapidly, and the negative is very nearly a horizontal line. This means that for the positive impulse a very small increment of voltage above the minimum value will produce a small reduction in the time to sparkover; whereas with the negative impulse the same small increment of voltage will reduce the time-to-sparkover by a large amount. Messrs. Davis and Bowdler have effected their sphere-gap calibration on the basis that 90 % of all the applied impulses cause sparkover on the gap. The American and German investigators, on the other hand, always work on the basis of a 50 % sparkover criterion. The change from 90 % to 50 % sparkover on negative polarity reduces the actual voltage of sparkover by a little, and the positive sparkover by a great deal; and the difference between the positive sparkover and the negative will diminish as the percentage sparkover is diminished. If Messrs. Davis and Bowdler had operated on a basis of 50 % for the criterion of sparkover they would not have found such high impulse ratios for sphere-gaps, either on negative or on positive polarity, and the difference between their negative and positive values would have been considerably lower.

With regard to the comparison of the impulse sparkover and the power-frequency sparkover, we must remember that the power-frequency voltage remains within 1 % of its maximum value for about 1 000 microseconds in each half-cycle, and, as Prof. Thornton has said, during this long time there are opportunities for electrons to get into the gap between the spheres and initiate breakdown. There are also many half-cycles in which this may occur if the voltage is increased slowly in the usual way. With impulse voltages, on the other hand, the voltage remains at its upper limit for only 1–2 microseconds: thus, if we are to compare impulse sparkover with power-frequency sparkover, we ought to take not the 90 % criterion of Messrs. Davis and Bowdler, or the 50 % of the American workers, but a criterion of, say, at most one part in 1 000; so that, for every 1 000 impulses we apply, only one causes breakdown of the sphere. We should then find that the voltage of sparkover for this criterion would be lower than the American value and much lower than that of Messrs. Davis and Bowdler, both on positive and on negative waves. I asked Mr. Smee a few days ago to test this for me, and he found that for one particular setting of the spark-gap, with the spacing equal to half the diameter of the spheres, the change from 90 % sparkover to 10 % sparkover was 2 % in the voltage for the negative impulse and 5 % to 6 % for the positive impulse. I am therefore unable to agree with Messrs. Davis and Bowdler's remark that the performance of a spark-gap on impulse sparkover cannot be deduced from the 50-cycle performance.

There still remains the interesting problem of why at certain spacings the power-frequency sparkover of a sphere-gap occurs sometimes in the negative half-cycle and sometimes in the positive half-cycle. I hope that the camera studies to which Messrs. Edwards and Smee refer will shortly enable us to clarify this fundamental issue.

Dr. C. Dannatt: Both sets of authors have used rather makeshift methods for the standardization of power-frequency voltages. Messrs. Davis and Bowdler have used an extrapolated value for the ratio of the transformer for their highest voltages, and Messrs. Edwards and Smee have employed an air condenser which is obviously inadequately screened, and to which they have ingeniously applied an empirical correction for the change of capacitance with voltage. For measurements such as those described in the papers, which entail great expenditure both in time and in the plant which is used, it is to be regretted that no effort has been made to develop a thoroughly-screened condenser for at least 1 000 000 volts. The compressed-air condenser can be made in fully-screened form for a voltage of 500 kV (eff.). The extension to higher voltages is limited by the difficulty of producing insulating tubes of large diameter and length capable of withstanding the high gas pressures which must be used. I believe, however, that this could be overcome by using two 500-kV condenser structures attached to a central steel chamber large enough to contain a 1 000 000-volt screened electrode system, and tensioning the central chamber at half voltage, in order to ensure correct distribution of voltage on the insulating tubes. Do not the authors think that it would be worth while to perfect some such development before any further work is done on 50-cycle flashovers at voltages of the order of 1 000 000 volts?

I should like to say a word regarding the effect of irregularities on the surfaces of electrodes in increasing the stress. When looking into this matter some time ago I came to the conclusion that the maximum stress at the surface of a cylinder, whose axis lies at right angles to a uniform electric field, is twice that of the uniform field; the corresponding ratio for a sphere is 3 times, and for an ellipsoid of revolution the increase is proportional to twice the ratio of the major and minor axes, the major axis lying in the field direction. Mr. Davis has said that a hemispherical irregularity on the surface of an electrode

would cause a 50 % increase in the average stress, but I think he will agree that it is the increase in the maximum stress which affects the breakdown, and this would be 200 % for the case he mentions.

The increase for a sharply pointed irregularity may be judged, from the case I have quoted for an ellipsoid, to be extremely high. I think that some of the discrepancies which still persist in high-voltage spark-gap calibrations may very probably be due to such surface irregularities. The very marked reductions which Messrs. Edwards and Smee observed in the breakdown by deliberately forming irregularities on sphere surfaces confirm this view.

Dr. E. H. Rayner: The sphere-gap cannot be regarded as anything but a makeshift, and at the National Physical Laboratory I was never enthusiastic about doing research on this subject merely in order to make minor improvements in the type of measurements employed for the purpose of passing machinery through a specified test. With the advent of the impulse generator, however, the sphere-gap has come to occupy an entirely new position.

Does industry ever use to any considerable extent a sphere-gap with both spheres insulated? In the references which I have seen to this matter the sphere-gap is not infrequently horizontal, and I should like to know whether the horizontal sphere-gap is liable to show slight differences as compared with the vertical one. No doubt the size of the room is of some importance in this connection. I should like to suggest that when we are trying to obtain consistent results it may be desirable for the high-voltage sphere to have a larger radius than the one at earth potential.

I notice that Messrs. Edwards and Smee found it useless to make outdoor tests; does not this suggest a possible reason for the divergent results obtained in different laboratories and at different times? Do we know that our indoor laboratories are sufficiently dust-free? Of the many impulse sparks which I have seen, not one has been straight. Is this due to dust? If so, it may account for divergences commonly obtained between consecutive readings.

Have tests been made to discover whether the fine-wire support shown in Fig. 1 of the paper by Messrs. Edwards and Smee tends to cause corona after the spheres have been in use for some time, and to alter the electric strength of the air?

Mr. F. M. Bruce: For the calibration of sphere-gaps at 50 cycles per sec. the authors have used the rectified condenser-current peak voltmeter as their standard of reference. Rectification was carried out with a mechanical rectifier, presumably of the commutator type, and I should be glad to know whether they have considered any possible errors due to the finite width of the brush-gear not allowing perfect rectification to occur at the instant the condenser current passes through the zero point. This adjustment may readily be made with suitably-biased thermionic rectifiers, and there is then no detectable difference between the measured values of the positive and negative half-waves. Were these values compared in the course of the present work?

The results of the condenser calibrations made by Messrs. Edwards and Smee indicate the influence of the potential of the second transformer tank upon the capacitance of the parallel-plate condenser, although Fig. 1 shows that the measuring disc is fairly well shielded from this tank by the high-voltage plate immediately above it. Another result is given on page 657 of the paper, where it is apparently assumed that there was no variation in the capacitance of the compressed-gas condenser with voltage, but on page 658 reference is made to a linear capacitance/voltage curve for this condenser. I should like to have some further information from the authors on these two points.

At King's College, Newcastle, we have compared a parallel-plate condenser—entirely free from corona, and with a known uniformly distributed field—against a compressed-air condenser by means of a Schering-bridge arrangement, the guard electrodes in both cases being directly earthed. In the first tests, neon tubes connected between the measuring-plates and earth were used as safety devices. Assuming that the compressed-air condenser has no variation in capacitance with voltage, the plate condenser increased in capacitance by 0·56 % as the voltage was raised from 10 kV to 200 kV. This was not a linear change, but appeared to approach an asymptotic value at the higher voltages. At no point could any difference in the power factors of the two condensers be noted. The neon tubes were now removed entirely, leaving only finely-separated air-gaps as safety devices. In this case there was no detectable change in capacitance (or power factor) with voltage. In view of these results it would be interesting to learn what form of protection the authors used on their bridge, and whether a "third arm" low-voltage network was employed. If the effects which I observed were due to poor insulation (or moisture effects) in the neon tubes or their holders, then similar effects could be expected on the light insulation referred to between the disc and guard ring. This is exposed to the atmosphere, and is connected between the same points as the neon tubes in the above tests. (The plate condenser used for them had an air space between the measuring disc and the guard ring.) The existence of a corona discharge between the plates of the high-voltage condenser would, I think, explain the effects which Messrs. Edwards and Smee observed, namely a linear increase in capacitance with voltage.

In selecting results for the calibration tables, reference is made to sequence diagrams. I should like to know whether there was any definite trend in the readings, and whether flashovers always occur between two very small areas on the surface of the spheres. The mean result for a band having a 2 % dispersion was used; does this refer to a deviation within 2 % from a series of equal high values, or from the mean curve of the sequence diagram?

I should like to know whether there was any tendency for vibration to occur during the 40 flashovers which were apparently required for each calibration point. As Dr. Rayner has said, it is very probable that corona discharge would appear on the steel rope from which the upper sphere was suspended, and this in itself might cause vibration, as it does in overhead transmission lines.

In the calibration of the sphere-gap on impulse voltages, some check measurements were made by comparison with a previously-calibrated gap. In this case were both gaps connected in parallel across the generator, and, if so, what were the relative percentage flashovers

taken as denoting a correct setting; or was one gap opened while a setting was obtained on the other?

The use of a 90 % criterion now appears to be normal practice. I should be glad to know of the reasons for its adoption, for a 50 % criterion not only appears to be more logical but it enables a reading to be taken with many fewer applications of the voltage. This may be an important consideration in avoiding undue strain on a test piece in parallel with the gap. In the latter case, what division of flashovers between the gap and the test piece would be taken as the true setting?

The authors used cathode-ray oscillograms having a maximum amplitude of 50 mm., and these were measured to an accuracy of ½ % or ¼ mm. As this is comparable with the thickness of the trace, I should be glad to know of any special method adopted in making this measurement.

On page 653, Messrs. Davis and Bowdler state that the corona in the set-up is much less for the impulse tests than for the power-frequency tests. Is this a conclusion based upon experimental work, or is it quite hypothetical? The duration of the impulse is so short that observation of corona by eye or ear alone might lead to incorrect conclusions on this point.

It is also stated that while no attempt was made to avoid corona, readings from 600 kV to 1 025 kV (peak) at 50 cycles per sec. were based upon an extrapolation of the curve giving the ratio of the testing transformer. I have observed the effect of corona on this ratio by introducing corona on to various parts of the high-voltage system and using several methods of high-voltage measurement. In this case there was a linear increase in the ratio of transformation with voltage until a point was reached at which a heavy discharge started from another part of the system. At this point there was a sharp increase in the slope of the line. Thus, if corona is not removed, then each voltage at which a new discharge commences will give an increase in the ratio of transformation, and even cause a discontinuity in the curve. This effect may increase in importance if there is no load on the transformer other than the gap under test. Did the authors use a water load or some such device?

I should be interested to know whether the cascaded transformers used by the authors of either paper took a leading current on the loads applied, for this effect is quite common when only one transformer is used to supply the voltage.

Mr. W. J. John: I shall confine my remarks almost exclusively to the paper by Messrs. Davis and Bowdler, since it deals with work of the type which we have recently been doing at Queen Mary College.

I have found the work which results in Fig. 2 to be particularly interesting. This Figure shows very clearly that the error in the recorded peak value of the voltage increases rapidly with decreasing tail-length of the impulse.

At Queen Mary College we have spent some time considering the polarity effect, and arrived at much the same kind of conclusion as Dr. Allibone. On page 649, in the first paragraph of the section headed "Polarity effects," the authors state that impulse flashover occurs most readily when the field at the positive electrode is strongest. In the subsequent work they show that flashover most frequently occurs when the field at the negative electrode is strongest. Why is the statement made and not discussed, particularly since the results contradict the statement?

Regarding the effect of wave-shape on flashover voltage, it should be worth mentioning that no difference in the recorded flashover voltage is obtained with different wave-shapes, provided the necessary correction is made from Fig. 2. The statement that no difference in the minimum impulse flashover voltage was obtained for the extremes of wave-shape employed, might in itself be misleading.

I feel that the authors dismiss the possibility of corona effects without giving it the attention which it warrants. As they took no particular trouble to eliminate corona, we must assume that corona discharge was present when the tests were being made. They state that corona effects could be neglected, because if they had been present the curves in Fig. 6 would have shown an increasing divergence. I should like the authors to amplify this statement: why should the curves show increasing divergence, and what is the shape of a typical curve when corona is present? Corona is very erratic in its effects, and Messrs. Edwards and Smee say that it sometimes increases and sometimes decreases the flashover voltage. We have found that it invariably increases the flashover voltage.

The most important point which emerges from the paper by Messrs. Davis and Bowdler is that the negative impulse flashover voltage was not equal to the power-frequency flashover voltage. This is in direct variance with the results of other workers, and requires confirmation.

Finally, regarding the paper by Messrs. Edwards and Smee, I should like to ask whether the spheres used in the tests were calibrated using the steel rope shown in Fig. 1. I suggest that a rather more orthodox arrangement should have been employed for supporting these spheres, since it is well known that discharges from the shanks supporting the sphere-gaps affect the flashover voltage.

Mr. A. M. Thomas and **Dr. A. W. Austen:** We are interested in Messrs. Davis and Bowdler's use of a liquid resistance for the purpose of standard measurements. They mention that the increase of the conductivity of liquids with stress is small at the stresses which they were using, but Raske* has recently pointed out that the conductivity of electrolytic solutions increases also with increase of the steepness of the impulse wave. Calculations made by Raske show that for electrolytes such as those employed by Messrs. Davis and Bowdler the increase of conductivity up to the frequency of a sine wave of length corresponding to the impulse wave would be negligibly small, but can it be assumed that a similar statement applies to those higher-frequency harmonics into which the impulse must be resolved?

There is also the possibility of electrode effects in such resistances. In d.c. experiments on a resistance potential-divider consisting of a solution of picric acid and phenol in an alcohol-benzene mixture, we have found considerable apparent decrease of resistivity with time in the neighbourhood of the electrodes. We do not infer that such effects occur with the much shorter times and the aqueous solutions used by the authors, but some

* *Archiv für Elektrotechnik*, 1937, vol. 31, p. 653.

evidence of the absence of such effects both in the impulse tests and in audio-frequency calibrating measurements would be desirable. In the absence of any electrode effects, and in view of the large temperature coefficient of resistivity of aqueous solutions, there might be some advantage in using a potential divider in which both elements are liquid resistances.

The use of bakelized-paper tubes for holding a salt solution is referred to by Messrs. Davis and Bowdler. We have recently attempted to use a varnish-paper tube filled with water as a current-limiting resistance. A brass cap terminal was employed which originally fitted loosely over the tube, but after a few days it was found to be almost impossible to remove the cap owing to the swelling of the tube due to the absorption of water.

Messrs. R. Davis and **G. W. Bowdler** (*in reply*): We are grateful to those taking part in the discussion for their contributions to the subject and for indicating possible obscurities in the paper. Prof. Thornton makes an impressive case for the parallel-plate condenser as an alternative to the sphere gap. Against it are the difficulty likely to be met in extending its use to measurements at higher voltages (300–1 000 kV) and the amount of leeway it would have to make up in the sphere of international standardization. We have not described experimental work with irradiated gaps, because our aim, as indicated in the second paragraph of the " Introduction," was to obtain calibrations under the conditions envisaged by national and international specifications. For small spheres with small gaps, where the volume of air in the field between the spheres is small, irradiation is likely to improve consistency. Dr. Whitehead's position on the I.E.C. Sub-Committee concerned with sphere-gap calibrations makes his historical survey authoritative, while his analysis of the experimental results is of great interest.

Our experience as to the dispersion of a.c. flashover voltages accords generally with that of Messrs. Edwards and Smee. Occasional low values are obtained, especially at the higher voltages; these values, however, were discarded, and the results given are the mean of about 10 observations all lying within ± 1 % of the recorded value. With impulse voltages the freak low values are absent, but the dispersion is about double that with alternating current.

At Dr. Allibone's suggestion we have determined for a number of cases the time-lag in breakdown with impulse voltages, measured from the instant the a.c. breakdown value is reached. The measurements show that the lag is approximately the same for positive and negative polarity, and that it increases with decreasing sphere diameter. Average figures for values of s/d up to $0 \cdot 5$ are $0 \cdot 9$ microsec. for 1 000-mm., and $2 \cdot 3$ microsec. for 250-mm. spheres.

Dr. Allibone's discussion of the polarity effect is both ingenious and plausible. We subsequently carried out some tests similar to those made for him by Mr. Smee. The relation between the magnitude of the impulse and the percentage of applications causing flashover was determined for 500-mm. spheres at a spacing equal to the radius. With positive polarity the change in magnitude to alter the percentage from 90 to 10 was $- 1 \cdot 1$ %, the corresponding figure for negative polarity being $- 0 \cdot 8$ %. When the magnitude causing 90 % of flashovers was reduced by $1 \cdot 7$ % for positive, and by $1 \cdot 2$ % for negative polarity, 40 applications of either polarity failed to cause flashover of the gap. These results, which are in general accordance with our experience throughout the tests described in the paper, indicate a much sharper transition from the non-flashover condition to that in which flashover occurs at each application than that reported by Dr. Allibone; they indicate also that if the calibrations were adjusted to the basis of a 50 % criterion instead of 90 %, the figures would require to be decreased by not more than $0 \cdot 5$ %. On the subject of the polarity effect, Mr. John points to our failure to rationalize the inconsistency between our experimental results and the remarks introducing that Section. We were careful to qualify the statements by the phrase " in general." Speculation based on general ideas is probably inadmissible in a severely experimental paper, but is perhaps permissible in subsequent discussion. We submit the following explanation for the experimental results—that when the polarity effects first become apparent the negative flashover value is lower than the positive. In the same way that the field at the surface of the high-voltage electrode is modified by the earth and by earthed objects, so is the field at the earthed sphere by objects (other than the other sphere) at high potential. When the value of s/d becomes sufficiently large, the influence of earthed objects on the high-voltage sphere predominates and the positive flashover figure is lower than the negative. For a certain critical range of values of s/d (beginning at about $0 \cdot 25$) the influence of objects at high voltage on the earthed sphere predominates and the negative flashover figure is lower than the positive. That the effect differs with different circuit arrangements the figures in the paper indicate. The difficulty of providing a quantitative explanation, requiring the calculation of field forms and the influence on them of neighbouring objects, needs no emphasis.

We submit to the strictures of Dr. Dannatt regarding the makeshift methods at present necessary for measuring the highest power-frequency voltages. He is to be congratulated on the suggested arrangement for a completely shielded condenser for 1 000 kV; we look forward to its taking practical shape. In this connection we would draw attention to the description by Binder* of a wire-wound resistor suitable for power-frequency voltage measurements up to 1 000 kV. We are also glad to observe that Dr. Dannatt concurs with our suggestion, made when reading the paper at the meeting, that some of the discrepancies which still persist in high-voltage spark-gap calibrations may be due to surface irregularities.

The influence of corona on sphere-gap calibrations is referred to by Mr. John and Mr. Bruce. For the power-frequency measurements the high-voltage circuit included a protective resistance of 200 000 ohms, consisting of a woven resistance strip. This was mounted in zigzag manner on a supporting framework, the whole being enclosed in a varnished paper tube. Corona on the resistor could be detected at about 300 kV (r.m.s.); the amount increased rapidly with voltage. The spheres were connected to the protective resistance by a relatively corona-free conductor at least 5 sphere-

* *Zeitschrift für technische Physik*, 1938, vol. 19, p. 48.

diameters long. The high-voltage conductors of the impulse-generator circuit were brass tubes 2 in. in diameter. Corona would thus be less with the impulse circuit than with the power frequency. Further, a finite time is required for corona to form, and this time might be comparable with the period during which the surge voltage exceeds the corona voltage. A dependence of transformer ratio on the corona in the circuit such as that reported by Mr. Bruce has not been observed by us. For a single transformer, and also for three transformers in cascade as far as measurements on the secondary side permitted, the transformer ratio increases from low excitations. At 20 % excitation the rate of increase falls, being practically zero from 30 % to 70 %; beyond this to full excitation the ratio decreases. We would add, parenthetically, at this point, in reply to a query of Dr. Allibone, that our extrapolation is made in the region where the ratio is approximately constant. As shown in Fig. 6, the impulse-voltage curves for the whole range of sphere sizes, when plotted for the variables V/d and s/d, approach a common limiting position for large values of d—a result in agreement with the deductions of Dr. Whitehead. A similar result is obtained with the a.c. curves, leading to the conclusion that no appreciable disturbing effects on the measurements can be attributed to corona, since such effects would increase rapidly with voltage and thus affect the values of V/d to an increasing extent as the value of d increases.

In reply to Mr. Bruce's inquiry as to the current taken by the cascade-connected transformers, we would state that for a small-capacitance load such as a sphere gap they take a lagging current, the power factor being approximately 0·9.

The use of a 90 % flashover criterion for minimum impulse flashover measurements was the accepted convention in this country up to the meeting of the International Electrotechnical Commission in June, 1937, when the figure was altered to 50 %. The reason for the original figure was, we believe, that it was considered that the minimum flashover characteristic of a test object should be that value of the voltage which caused sparkover nearly every time. As a 100 % criterion would not have fixed the upper limit of voltage precisely, the value in question was selected. We do not agree with Mr. Bruce that the use of a 50 % criterion would enable an observation to be made with fewer voltage applications than if the 90 % criterion were used. With regard to the question of the logical basis for any particular criterion, we refer him to Dr. Allibone's remarks. When a test-piece is connected in parallel with the measuring gap, the magnitude of the voltage is adjusted to the minimum flashover value, with the measuring gap not breaking down. The gap is then adjusted until flashovers are equally distributed between the test-piece and the gap.

With regard to the question of the measurement of oscillograms, the width of the trace with a well-focused beam is about 0·3 mm., and with a steel rule and a watchmaker's lens it is not difficult to estimate the centre of the trace to 0·1 mm. No appreciable increase in accuracy is gained by the use of a travelling microscope of low power.

As Mr. Thomas and Dr. Austin point out, the accuracy of the impulse measurements depends on the assumption that the electrolytic resistors used as the high-voltage arm of the voltage divider obey Ohm's law under the conditions of use. They refer to the work of Raske,* pointing out that the conductivity of electrolytes increases with the steepness of the impulse wave. Mr. Thomas and Dr. Austin appear to have misread the paper in question. Raske found the effect to be negligible for a sine wave which was equal, not to the length of the surge, but to twice the length of the front of the surge (*stoss-stirn*), i.e. he represented the front of the impulse as half a sine wave and showed that for this rapid rate of change of voltage the increase in conductivity was negligible.

We have generally avoided in impulse-voltage measurements the use of wire-wound resistances requiring a long conductor, because of the difficulty of predicting the transient response. Recently, however, we constructed several resistors by mounting woven resistance ribbon longitudinally on cylindrical insulating tubes, which the ribbon almost circumscribed. Oscillograph records of minimum impulse flashover were almost identical with those obtained with an electrolytic resistor of about the same value, while the determined magnitudes were the same in the two cases within the limits of experimental error. For most of the measurements described in the paper an electrolytic resistance was used as the high-voltage arm of the divider, generally sodium-chloride solution. For the lower-voltage measurements the electrolyte was contained in a glass tube 5 ft. long; for the higher, requiring longer containers, a varnished paper tube 12 ft. long and 2 in. bore, and 1 in. bore rubber hose, were used successfully, care being taken to maintain the electrodes clean and free from sharp edges, so that sparking in the electrolyte would not occur at high voltage gradients. After allowing for errors due to earth capacitance, the results obtained with resistors ranging from 7 000 to 100 000 ohms agreed within the limits of experimental error. Generally a value of 10 000 ohms was chosen, for which the errors were negligible.

Messrs. F. S. Edwards and **J. F. Smee** (*in reply*): Owing to the large amount of ground which is common to our own paper and that of Messrs. Davis and Bowdler it is not always easy to determine where our reply should begin and end. We have not attempted, therefore, rigorously to segregate the remarks into comments (*a*) on the paper dealing mainly with 50-cycle calibration and (*b*) on the paper dealing mainly with impulse calibration, with the intention of omitting any reply to comments under (*b*), but have dealt with each point from the aspect of its application (if any) to the calibration of the sphere-gap at 50 cycles per sec.

In general, the discussion does not appear to have revealed any serious disagreement with the methods we adopted and the conclusions we reached; certain points of detail have, of course, as is inevitable, occasioned suggestions or even mild criticisms, but we are glad to find that we have not been charged with the commission of any fundamental blunder.

Prof. Thornton refers to the valuable work carried out by Dr. Stephenson in which parallel-plate electrodes with specially shaped edges were employed. Astonishingly

* *Loc. cit.*

consistent results have been obtained for the breakdown voltage of air-gaps in this way, partly owing to the automatic shielding of the gap provided by the particular electrodes used, partly owing to their relatively large sparking area as a function of the gap spacing, and partly on account of the great uniformity of their field. We cannot agree completely with Prof. Thornton's statement that the results can be calculated for parallel-plate electrodes. Undoubtedly that particular configuration approaches much more nearly than a sphere-gap to an ideally uniform field, and to that extent lends itself more readily to calculation, but surely the second term in the non-linear expression representing voltage as a function of spacing is really an empirical one. The points which we had in mind in our reference to the vain pursuit of a satisfactory expression connecting the breakdown voltage with the spacing of a sphere-gap were that the proximity of neighbouring objects introduced an incalculable factor and that the "apparent electric strength of air was a function of the curvature of the electrode surface." Prof. Thornton takes exception to the latter statement. It is used repeatedly by Peek, however, and we therefore considered it unnecessary to explain in detail precisely what it meant, especially as we had expressly disclaimed any intention of discussing the theory of the field in a sphere spark-gap. As Dr. Whitehead remarks, the general tendency nowadays is to adopt "the principle of experimental calibrations" rather than "the attitude that calibrations should be calculated from Peek's formula," and this bears out our own statement that no theoretical formulae have so far been evolved which have not subsequently proved to be wrong.

The practical difficulties involved as a result of the large size of parallel-plate electrodes, and the extreme care required in setting-up and levelling such electrodes, which must be rigid and are necessarily very heavy, tend to militate against their usefulness except under favourable laboratory conditions. Incidentally, we are not very sanguine regarding the caged gaps and guard rings on which Dr. Whitehead asks our opinion. Our experience in this matter we must admit to be very limited, but the complications involved in the erection of such gaps compared with the simplicity of a simple sphere-gap seem to us to be too great to justify their use.

If we might stray for a moment from our own particular province, we would suggest that as the spread of the sparking area on parallel-plate electrodes is (as stated by Prof. Thornton) 500 to 1 000 times as great as with spheres, then the difference between 90 %, 50 %, and 1 in 1 000 sparking under impulse voltage which is obtained on spheres (mentioned by Dr. Allibone) should be greatly reduced, and the 50-cycle figure should practically coincide with the negative-impulse figure. It would be of great interest if this point could be verified when the calibrations referred to by Prof. Thornton in the conclusion to his remarks are carried out.

Dr. Whitehead's recapitulation of the progress of sphere-gap calibration in various countries during the last 12 years is of great interest and value, and the figures he quotes of the small differences which still separate the calibrations in various countries lead us to hope that agreement may soon be reached in this sphere at least of international relations. We note with satisfaction that our own figures appear in general to show no marked inconsistencies between themselves when subjected to the theoretical examination and analysis described by Dr. Whitehead. The frank explanation put forward by the latter for the low figures which he obtained some years ago on the 6·25-cm. spheres is very gratifying, as it disposes of the one seriously divergent calibration for this size of sphere-gap.

Dr. Whitehead asks whether we recommend for standard use the selection of certain results out of a batch. We certainly do, on the lines proposed in the paper, and as explained in our reply to Mr. Bruce.

In reply to Dr. Allibone, the number of observations taken to plot one point on a polarity curve varied considerably. In the region where all the breakdowns were expected to be (and in fact were) of one sign only, perhaps 20 readings were taken, but in the uncertainty region the number was increased to perhaps 50. His explanation of the discrepancies between the four sets of independent results sounds plausible and may quite probably be right, but we hope to do some further work on the subject.

Dr. Dannatt makes the proposal that the cascade-connected transformer which we used might be employed to provide a mid-potential support for a fully screened million-volt condenser consisting virtually of two 500-kV condensers. Such a piece of apparatus would be very valuable, but whether the development would be really justifiable is in our opinion a little doubtful. When the question of the metering of power supplies is involved then obviously the accurate measuring of the voltage is highly important, but in the region above about 400 kV the voltage is only required for pressure and breakdown tests and an error of 1 % or 2 % does not really matter from a practical point of view.

Dr. Rayner describes the sphere-gap as a makeshift, and we agree with him, but, as he points out, there is no satisfactory alternative at the present time, especially in connection with impulse work. He inquires with regard to the applications of sphere-gaps with both spheres insulated. These have a limited field of use in connection with high-voltage X-ray equipments at the present time, but whether their use will grow depends upon electrical developments which we cannot at the moment foresee. The horizontal sphere-gaps to which he refers are used mainly in the smaller sizes (up to 25 cm. diameter), chiefly for convenience in construction, and when suitably designed they give results in close agreement with those obtained on vertical gaps. The question of dust and its effects on the results is of interest, but we do not consider that it provides an adequate explanation of the discrepancies between the results obtained by various laboratories. We found that dust in large quantities produced numerous low freak values, and for that reason we abandoned outdoor work, but if an examination of a series of readings shows that most of them lie within a narrow band, with a few lower readings, then we think that the readings within the band are correct and not affected by dust. If a 2 % dispersion band containing all the highest readings only included a small percentage of the total readings, then we might assume that the true value was still higher and that the readings could not be relied upon.

Mr. Bruce asks for certain details of the rectifier used

for the crest voltmeter. The rectifier itself permits adjustment to 0·5 electrical degree, so that the error due to a finite brush-width can be ignored. Our reference to "a linear capacitance/voltage curve for the compressed-gas condenser" was perhaps not sufficiently explicit, and justifies Mr. Bruce's request for an explanation. As he points out, we had stated previously that the capacitance of this condenser was independent of the voltage, and although it is strictly accurate, therefore, to describe it as a linear function of the voltage, nevertheless the erroneous idea is conveyed that the capacitance itself actually changed with voltage.

The central disc of the upper electrode of the million-volt air condenser is described in the paper as "lightly insulated from the outer and rounded portion which forms the guard ring." The term "lightly insulated," on which Mr. Bruce bases certain observations, is relative only. Actually the insulation consisted of high-voltage suspension insulators, and as there are steam pipes in the roof of the building which are kept hot all the year round there is a negligible chance of condensation; so that we do not consider it at all likely that any error arose due to this cause during the measurements. Spark-gaps were used as protective devices during the Schering-bridge tests.

In regard to the question of vibration, the upper sphere sometimes began to swing during the tests, but if this occurred the sphere was allowed to come to rest before the tests were resumed.

When sequence diagrams were plotted the general tendency was for the first few shots to be low and for the results thereafter to be higher and reasonably consistent, with occasional low "freak" shots. The results from which the calibration charts were drawn were the means of those values not less than 2 % below the maximum value obtained.

In general, the sparking occurred over a very limited area. It can be readily shown that at a spacing equal to the sphere radius an area round the sparking tip of radius $0 \cdot 1R$ (approx.) encloses the whole of the surface within which the gap is not more than 1 % in excess of the shortest distance between the spheres. One might reasonably expect, therefore, that the sparking should be distributed over an area of this size or perhaps a little larger. Mr. Bruce asks another question, but we are not quite certain whether it is intended for Messrs. Davis and Bowdler or ourselves. It concerns impulse calibrations and we assume that it refers to the brief statement on page 635 that the voltage at which the rapid change in the polarity characteristic occurred at 50 cycles per sec. coincided almost exactly with the voltage at which the positive- and negative-impulse calibration curves crossed. In this case 100-cm. spheres were used as a (presumably) non-polarized impulse-voltage indicator (since the gap did not exceed about 20 cm.) and the 25-cm. gap was adjusted until the sparking was divided equally between the two sphere-gaps. Incidentally, great care had to be taken to ensure that the true minimum impulse voltage was being applied, as a slightly excessive voltage transferred all the breakdowns to the larger-diameter sphere-gap on account of the much shorter time-lag of the latter. (It must be remembered that the smaller-diameter sphere-gap was being tested at spacings up to 2 diameters.)

As regards the cascade-connected transformers, the power factor in the second transformer was probably slightly leading, but the rating of these transformers is so high (500 kVA each) that the charging current of any ordinary high-voltage load is not sufficient to affect their performance seriously.

Mr. John does not like steel ropes as a means of support for spheres. Tests (not quoted in the paper) had shown some time ago, however, that although a thin steel rope suspension did not give the highest results on 100-cm. spheres the values obtained were only about 1 % lower than those found when a metal cylinder 8 in. diameter was placed round the upper shank. Smaller sizes of cylinder gave lower results than the wire, and so it was decided to employ the wire suspension in view of its great simplicity. These results cast a doubt on the requirements of B.S.S. No. 358—1929, in which it is stipulated that the shank diameter should be between 0·1 and 0·2 of the sphere diameter, and we think that this particular section of the Specification should be reconsidered.

DISCUSSION ON "ORGANIZATION OF A METER TEST DEPARTMENT OF A LARGE SUPPLY UNDERTAKING, WITH SPECIAL REFERENCE TO THE ELECTRICITY SUPPLY (METERS) ACT, 1936"*

NORTH-WESTERN CENTRE, AT MANCHESTER, 1ST FEBRUARY, 1938

Mr. J. B. Lees: In my opinion the author attaches too much importance to the value of off-circuit testing as a routine procedure. I hold the view that accuracy testing of off-circuit meters has no value, and consider that he is misguided in allowing this work to affect his method of handling these meters. For example, 50 meters of the same type, size, and make, left on circuit for 5 to 10 years, could easily show differences in consumption of the order of 10 : 1. In addition, it has been established that the loads on which a meter is operated have a profound effect on its resultant condition and accuracy. With the rateable-value type of consumer one meter might operate on 200 watts and another on 2 000 watts for most of their lives. This lack of uniformity in the conditions under which meters operate on circuit is responsible for my views on off-circuit testing.

I suggest that the correct way to handle a meter removed from circuit is to clean it externally in a room separate from the repair room, and then deal with it in the repair room as a watchmaker would a watch. There is no doubt that a mechanic produces better work when sitting down, on a comfortable seat of comfortable height, with one meter in front of him, and one only, rather than when standing before a test bench.

In the meter department with which I was associated a few years ago each repairer was provided with a shallow framed piece of plate glass measuring 18 in. by 12 in. Having cleaned the glass he commenced work under watchmakers' conditions, removing first the train and then the rotor and bearings. After cleaning the jewel he examined it under a microscope with magnification of 50 and Lieberkuhn illumination. The pivot was examined with a pocket microscope giving a magnification of 25, and in a profile projector with a magnification of 200. My experience is that profile examination is essential. After the train had been thoroughly overhauled it was considered satisfactory if the worm wheel could be rotated from the 5th driver, i.e. the fifth wheel in the train from the worm wheel. All faults discovered were logged on a card which already carried details of the meter's number, state, type, where removed from, etc., these details having been entered by the meter fixer. With such an organization the engineer in charge was easily able to inspect the cards for the day and determine what faults were arising on circuit.

The author refers to the desirability of harmonious flow. In an undertaking dealing with 1 000 meters per week this is imperative, and in my opinion can only be obtained from the best possible work in the repair room.

I am still convinced that the most rapid method of testing meters is by stop-watch on held loads. The position is, however, now influenced by the fact that the Electricity Commission's meter examiner is authorized to select any quantity from any batch. In a large undertaking with ample test-room accommodation it may be found desirable to leave tested meters on test racks to await certification. Under such conditions the long testing-time inherent in dial-testing loses its disadvantages. On the score of accuracy there is no real disadvantage in stop-watch testing. It may be interesting to record that, when testing a selection from the first batch of 169 meters we submitted for certification, the examiner did not find a greater difference from the logged results than 0·2 %. It is my experience that this difference is quite normal in repeated tests.

With reference to Fig. 3, it would be interesting to know how many meters of Make "A" were analysed. I should also like details of the total personnel required for dealing with 1 000 meters per week.

Mr. W. D. Sutcliffe: Of the various methods of testing I think method "A" is the best for large undertakings where meters can be put up in batches of 200; but the accuracy of meters has a considerable bearing on this method, and if more than 10 % require adjusting method "A" is not worth while. This, in my opinion, is where the manufacturers come into the question, because accuracy will influence buying very considerably. There is very little to choose between any of the modern meters in the matter of material and workmanship. Method B should not, in my opinion, be allowed by the Commissioners at all, and the experience of examiners will prove this to be the least accurate of the three methods. Of meters received from manufacturers which have been tested by that method we have had as many as 60 % rejected. Method C is quite sound, and experience shows that with this method loads can be held and tests repeated within very small limits. This was the father of all the other methods, and is the one used by the examiner in his check tests.

The only point regarding the author's method of testing off-circuit meters about which I have a doubt is the paint spraying. I should like to know what happens to the small part of the cover where the front case meets the back case.

I do not recommend the universal adoption of the method shown in Fig. 1, as in some instances the mains voltage of 400 volts appears to be available inside the meter, between the voltage and current coils. I think this arrangement ought not to be used in test circuits, and I would recommend the insertion of a double-wound transformer.

The author says that the Commissioners have laid down stringent specifications for standardizing instru-

* Paper by Mr. C. W. Hughes (see page 410.)

ments; but the errors allowed on those standards are too high, particularly the phase angles in wattmeters.

Touching on Section (2), I agree with the author about keeping records of faults on circuit, but very much doubt whether the cost of obtaining the off-circuit test records is worth while. As meters will presumably have to be removed every 10 years in future, those records cannot serve very much purpose. We shall be so busy removing meters that 2-year removals will be out of the question.

We enter the records of test results directly into the test book, and this is the only record made. When we are using Method A we run all the tests for one unit, the test books are sent into the office, and the typist can immediately extract the percentage error from the book without having to make a calculation. If the meter reads 1 it is correct, and if 1·01 it is 1 % high; the typist can see at a glance what the percentage error is.

Mr. J. L. Carr: The paper has come at an opportune time, following the publication of the Commissioners' requirements for meter testing. Three distinct test methods have been laid down, each of which has something in its favour under certain conditions; but frequently, when dealing with small quantities of meters of a particular size, it may be found that a combination of the methods gives the best results. For large quantities of meters of uniform rating, probably the simplest and cheapest method to adopt is "A," but the time required for low-load tests holds up the equipment seriously.

The layout of the test equipment described by the author is very simple; but I do not care for the use of plug connections in the voltage circuit. A knife switch is preferable; and, though probably more costly, it removes the possibility of troubles associated with flexible leads and plug connections.

Regarding the question of costs, the author calls attention to the fact that establishment and overhead charges are usually a very serious item in the cost of testing meters. The importance of these standing charges is not generally realized. After a careful analysis, I came some time ago to the conclusion that, apart from the actual cost of testing and electricity, the latter being taken as negligible, the fixed costs, including stores and handling, amounted roughly to 1s. 10d. per single-phase meter. The cost of handling meters in stores was slightly higher than the 2·5d. given by the author; and recording costs were practically identical with the figure given in the paper. The cost for new meters of transport to test bench, connecting up, testing, adjusting where necessary, disconnecting, and removal to meter stores, amounts to 3d. a meter according to the author. This figure seems extremely low, particularly compared with 2·5d. for handling in stores, and requires verification.

Again, for "reconditioning of meter elements" the cost is given as 8½d. for labour and 1¾d. for material. This figure is so low that it must presumably represent the average cost of attention to every off-circuit meter, and not that representing a comprehensive overhaul of defective meters only: the latter figure runs into shillings.

With regard to methods, the accuracy of the testing of meters against rotating substandards depends to some extent upon the inherent accuracy of the substandard: frequently types have been employed which have been subject to considerable errors due to self-heating and temperature. Other types have been available, and are now becoming available in this country, in which the performance is of a high order; and final accuracy of meters tested by this method against proper substandards should be at least as high as that attainable by other methods.

I have been concerned for some time at the cost of handling meters, and the possibility of adopting in the electricity supply test-room some improved method: the problem is not, however, so simple here as in a manufacturer's works. The author unfortunately does not refer to this important aspect.

Mr. O. Howarth: The tests required by the Commissioners do not, in my opinion, show the accuracy of a meter, because they are insufficient. They only ask for one test at a power factor of 0·5 lagging, and that at full current, which is not characteristic of the general error of the meter at 0·5 lagging. There is no provision for a double-load test, which I imagine most undertakings are using.

There are quite a number of 2-element 3-phase 4-wire meters in use, and the Commissioners will allow them to continue to be used. The polyphase testing arrangements of Fig. 2 does not meet the condition that a 2-element meter assumes—that the sum of the three voltages on the three separate phases is zero. It is not an unusual equipment in that respect, because none of the manufacturers' equipments that I have seen has made provision to ensure that condition, which is essential if one is to test satisfactorily a 3-phase 4-wire 2-element meter.

In the author's testing equipment the testing racks seem to be constructed with the shelf at about waist level. We have put the shelf 2 ft. up from the floor, which enables the testers to sit with their knees underneath it, and have put a row of meters quite low down and other rows higher up. This arrangement makes for greater comfort, and greater comfort in testing undoubtedly means greater accuracy.

With reference to Tables 1 and 2, it is interesting to consider what is going to happen when the appointed day arrives on which certified meters go out into service and we are not allowed to break their seals. Information as to their accuracy will only be obtainable when the meters come in off circuit, because we shall not be allowed to break the seals, except those of slot meters.

Mr. A. M. Strickland: The author states that one tester can take the readings on long-period dial tests; I have found it quicker and much more reliable for one person to read while another writes down, because it is not very easy to take a reading and then look down to make the entry on the sheet, especially if one is working rapidly. The subsequent computing of the results entails considerable work, and where it is feasible and the cover is of the non-magnetic type and may therefore be left off, it is often advisable to reset the dials after each reading. Another disadvantage of the

long-period dial test is that it becomes rather difficult to accommodate meters having large cases, owing to the very large area of rack space required.

The author states that repaired meters will have been already calibrated by disc-revolution methods, and in Section (4) he refers to the need for a stroboscopic device for calibration purposes. I have endeavoured to develop such methods, but of course they do not apply to low loads where calibration by watch methods is used after full load has been adjusted. The zero-lag is first adjusted, then the meters are made to stand still under a stroboscopic light (obtained from a small neon lamp with 50-cycle supply from mains, or 25-cycle supply with half-wave rectifier) and a purely arbitrary load is held on the wattmeter. This load is determined solely on the basis of giving close-accuracy results in the finally-tested meters, and makes allowance for different types and for covers being removed during the calibration. With properly-trained men on such work and combining the necessary repair work, it should be possible to develop methods of taking "as removed" tests, doing the necessary work on the meter, and passing it with very few failures to a final test equipment. The rotating-substandard method will continue to be handicapped so long as we have to contend with meters of so many different speeds, and I suggest that meter speeds could well be standardized to some degree by the manufacturers.

With regard to the question of load-holding (Method "C"), I hope that it will be possible to develop apparatus capable of holding a load automatically and very accurately. Since this item is so important it is a pity it is so often assumed that less skilled persons will suffice for this part of the work.

The author states on page 411 that the only true test of a meter's performance on site is one taken under working conditions. It would appear that even with the new Act in operation there will still be a field for employing some on-site tests to make sure that revenue losses do not occur on low loads.

The equipment shown in Fig. 1 appears to place a considerable secondary burden on the current transformer, since precision is highly desirable. Has the author not considered the use of a separate core to supply the non-precision part of the apparatus?

On page 413 the author points out that the new Act does not refer to the testing-station personnel. It is perhaps unfortunate that the Act is so worded that individual meter certification is involved, since (in common with many other persons) I believe that a general control would have had the desired results of ensuring uniformly good metering. I would point out that a large proportion of responsible meter engineers have not been unmindful of their duty to give correct metering of supplies, and that some strengthening of their position, together with the assistance which the examiners could render, would probably have sufficed to ensure greater uniform accuracy.

I consider that the author has omitted a very important factor with regard to the possible re-test period of meters (page 415). It is that the climatic and general conditions are important since meters used in a very damp and dusty area will give vastly different results from those obtained in cleaner areas. Salty atmospheres at the seaside have their effect.

On the same page the author refers to "modal accuracy." Would he care to explain the term further?

Mr. E. Roscoe: My opinion of method "A" (the dial-test method) is that it is the cheapest for finding what are the errors of a fairly large number of meters, but I do not think it is the best for making these meters register within definite limits of error, or that it gives greater accuracy than that obtainable by the stop-watch method. As has been pointed out, this is the method used by examiners for checking purposes.

Consistency is one of the chief gauges of quality of a meter now that re-testing for certification is necessary. One of the main causes of inconsistency is mechanical troubles in bearing surfaces. These cannot be found by method "A," as so little of the train has been in operation during the registration of 1 unit. Most makes of meters call for greater attention to be paid to the finish of the spindles and bearings, including the top and bottom pivots and the jewel. Some quite cheap watches have a number of jewelled bearings, and one is fitted with a very fine ballrace. These may eventually find their way into meter trains.

It is desirable that the handle should be so placed that when the meter is carried the pivot is off the jewel, thus avoiding the blow on the jewel which normally occurs each time the meter is put down clumsily. Further, provision of a 5-way terminal block in meters is long overdue.

I should be interested to have more information about the spraying of the edges of the covers, as these are the most common places where the paint may deteriorate and fall into the meter.

I agree with Mr. Sutcliffe as to the danger to the tester of drawing current direct from the mains.

The Commissioners are very lenient in requiring a test at only one load at 0·5 lagging power factor; I should like to have the author's views on this requirement. Another interesting piece of information would be the particulars of the staff necessary to deal with 1 000 meters per week. Does this figure include off-circuit meters?

Collecting statistics on off-circuit meters can take much time, and often when one has found where the trouble lies the design is out of date. The speed with which designs are changed is shown by the fact that unless one sends a sample with an order for spares the new parts do not fit.

Finally, it would be of interest to know more of the general organization of the author's test-room, since he states that it is governed to some extent by the method adopted for testing house-service meters.

Mr. S. R. Mellonie: I am surprised to see that a voltage regulator is shown in Fig. 2; in these days of automatic on-load tap-changers is not the supply from a very well-regulated 400-volt network satisfactory? A supply taken direct from either a 6·6-kV or an 11-kV busbar is a very uneconomical proposition, because it means allotting a quite expensive piece of switchgear to feed a relatively small transformer (100 or 200 kVA).

The author refers to the difficulty of dealing with dirt, and I should welcome his opinion on the question of

whether air-conditioning plant is not the right solution under the conditions which obtain in industrial centres.

The advent of the 1936 Act has caused considerable expenditure on test-room equipment to produce a "certified" kilowatt-hour meter which registers units only, and it is instructive to consider what proportion of the revenue is based on the readings of the kilowatt-hour dials. The figures of an industrial undertaking show that no less than 31 % of the total revenue is either based on the reading of the maximum-demand indicator or is related to some convenient basis, such as rateable value, and is independent of the meter reading as covered by the Act. In the case of large power users the charge based on the maximum-demand indicator reading is about equal to the amount charged on the unit reading.

Quite apart from such considerations, we have to face the fact that the diversity factor is a good deal more important than the load factor in many cases. What is more, voltage regulation is a very real factor in the value of the energy delivered to the consumer using heating and cooking appliances. These important considerations are not taken into account by any practical measuring device, but serve to emphasize the limitations of the legalized meter. Again, the units are frequently read from as many as six dials, whereas generally speaking it is impossible to read a maximum-demand indicator to more than three figures, and the reading is often multiplied by 5, 6, 7, or 8, for the appropriate kilowatt charge.

I would suggest that, in view of the fact that the charges on the two readings may be about equal, there is room for improvement in equalizing the accuracy of the two sets of meter readings.

Mr. W. Fennell: The object of the Electricity Supply (Meters) Act was not really to increase the accuracy of meters, but to ensure a certified meter reading to which one could swear in court. I think the Act achieves that object. For the rest, I do not think anyone expects there will be any increase in accuracy, or that any very great increase in accuracy was necessary.

By way of supporting the wisdom of the Commissioners in making one test under method "B" a dial test, I will mention something that happened to me when I first came to the North of England. I found that a certain consumer was constantly complaining that his meter was reading very high. I was able to point out to him that the consumption in his house was below the average of the terrace where he lived. He replied "Yes, but I am very economical." I tried to satisfy him that he was wrong by mentioning that his type of meter could not speed up. About a year later he renewed his complaint, and in view of his persistence I decided to have the meter inspected carefully, although he had not demanded a test. When the meter was brought in to the test-room it was found to be reading exactly 100 % high! It was a 440-volt d.c. meter which had been marked "220 volts" by the makers.

Mr. P. Clegg: One point I wish to dispute with the author is his method of off-circuit testing. I agree with a number of previous speakers that the off-circuit test has not as much value as the author attaches to it. In the first place, he is using the test for trying to determine the numbers of years' service obtainable from different makes of meters; but such matters as the make and size of the meter are not the determining factors in deciding what should be the length of life of the meter. The meter does not register time; it registers units, and therefore the more important matter is the number of units registered rather than the length of time the meter has been in use.

When dealing with the off-circuit test the author mentions the testing of a number of samples of the meters entering the test room. This is not satisfactory because there are generally so many types of meters, made by different manufacturers, in use. The solution is for the supply undertaking to use only one make of meter.

It has been determined by the Act that the official test is to be the test made by the supply authority, and this test overlaps to a certain extent that carried out by the manufacturer. It appears to me that there should be some arrangement between the manufacturers and the supply industry whereby this overlapping of tests could be avoided. Such an arrangement would probably lead to a reduction in the price of meters, which is what the supply industry requires.

Mr. J. H. Buchanan: In Fig. 1 the author has a variable resistance in series with the primary of the supply transformer. Does he consider this arrangement satisfactory, in view of the possibility of the series resistance introducing distortion of the wave-shape?

Mr. A. H. Gray: On page 415 the author states "The omissions from a maker's catalogue often speak more eloquently than the data provided." This statement is worthy of amplification, and I should appreciate some more details concerning these omissions.

The most vulnerable parts of meters are, of course, the pivots and jewels, and these will need special examination. I should like to know whether the author has any particular method of carrying out this examination; for example, does he use the microscope or needle for this work? Another important point is the question of lubrication; I should welcome his comments regarding his lubrication specification.

With regard to the controversial subject of off-circuit tests, Mr. Clegg has referred to the fact that the meter primarily measures kilowatt-hours, and hence these should be a measure of the life of the meter, rather than a time basis. I would point out, however, that kilowatt-hours are not in themselves a measure of wear, and hence may produce entirely fictitious results. It is well known that the pivot and jewel are subject to wear due to both rotation and vibration; hence it would seem that both kWh and time (this latter as a measure of the wear due to vibration) must enter into a correct basis of wear.

Another important feature of meter testing I should like to raise is that of site testing, which is largely favoured in America. This method has much to commend it in the case of large metering equipments. I do not suggest that site tests should obviate the laboratory or works tests, since site conditions can rarely provide the same degree of accuracy, but I do consider that they will prove a useful indication that the equipment is maintaining the initial accuracy. Perhaps the author would tell us of his experiences in this direction.

Finally, I should like to raise a point in connection with Mr. Mellonie's remarks concerning the accuracy of maximum-demand indicators. Admittedly, these indicators do not give so accurate a reading as the units measurement, but I would stress the fact that this inaccuracy is aggravated in a large percentage of cases by the fact that the equipment has too high a capacity for the loading conditions.

THE AUTHOR'S REPLY TO THE DISCUSSIONS BEFORE THE METER AND INSTRUMENT SECTION (SEE PAGE 421) AND THE NORTH-WESTERN CENTRE

Mr. C. W. Hughes (*in reply*):

Testing-methods A, B, and C.

There is undoubtedly a diversity of opinion as to which of the three methods laid down is the best. Several speakers support the statement on page 411, par. 7, of the paper, that for small quantities of meters methods B and C are the most economical. To this might be added that those methods are probably also most economical for dealing with old meters fitted with non-standard dials. It must be remembered, however, that the paper refers only to large undertakings, where large batches of meters of the same size and type are dealt with; and though many speakers state that methods B and C are just as good as method A, practically no arguments have been brought forward to support this contention. Mr. Howarth raises the point that intermittent gearing trouble may not be revealed by light-load dial test, which only gives the mean accuracy over a long period. The short-period test would reveal the trouble if the test took place at the critical point in the gearing, but the odds are very greatly against this happening. The ideal method would be a great number of short-duration tests, but that is impracticable when dealing with large numbers of meters. The light-load dial run will give the mean accuracy at that load and, after all, it is the mean accuracy which matters for purposes of payment.

It is admitted that method A does not entail a complete revolution of all wheels in the counting train, but it does test thoroughly all the fast-moving wheels in which the presence of mechanical imperfections are most serious. The fast-moving wheels are also those which have to be changed for different sizes of meters, and therefore they are the wheels most likely to be wrong in gearing ratio.

Mr. Page points out that an error in reading of 0·1 % at full load would cause an error of 1 % at 1/10th load, but according to the Commissioners' requirements the light-load dial test would be at 5 % full load, and the error would then be 2 %. This should be apparent. The same speaker advocates the use of motor-generator sets or valve stabilizing equipment for use with method C; but there does not appear to be any justification for expenditure of this nature when it can be avoided by using method A. Simplicity should be the keynote of all test-bench design, all unnecessary contacts and complicated mechanisms being eliminated. If it is necessary to have contacts or other mechanism, they should be of such a nature that their failure cannot affect the accuracy of the calibrations being carried out on the bench.

The question of self-heating due to the series coil, raised by Mr. Muir, is of importance when testing certain makes of meters, the inaccuracy possible being as much as 0·5 %.

I cannot agree with Mr. Hill that by using rotating substandard meters instead of wattmeters and stop-watches, the stop-watch error is simply moved one step back and will therefore be common to more meters, as other factors must be taken into consideration. Mr. Golds describes a method by which stop-watches are cut out altogether, and this is undoubtedly to be recommended. But even if stop-watches are used for testing the substandards, they are used by persons of superior skill and get less wear and tear than when used directly for meter-testing. Also, since the number of substandards is small compared with the total number of meters tested, more time can be spent repeating results and checking the watches, so that the errors should be practically eliminated.

Off-circuit testing and analysis of results.

I have been at some length to explain that the off-circuit tests, so far as they relate to individual meters, are of no value for the purpose of proving the accuracy of that meter while fixed in the consumer's premises, but that, taken collectively, they are of value as giving an indication of the general condition of meters on circuit. Above all, it has never been assumed, as Mr. Richards seems to imagine, that the value of this test is enhanced by previously cleaning the meter externally. It simply happens that the sequence of operations given tends to less handling and an easier flow than any other sequence, with the test methods adopted. That the handling due to external cleaning makes very little difference to the total result is borne out by the fact that 100 meters which were tested before cleaning gave a modal accuracy of 100·5 % at full load and 100·1 % at 5 % of full load, and the same meters, after cleaning externally and painting, gave a modal accuracy of 100·6 % at full load and 100·5 % at 5 % of full load. One or two individual meters showed large variations between these two tests, owing to dirt being shaken out of or into the magnet gaps, but as the mode takes no account of large individual variations, they do not, fortunately, affect the final result.

The value of the off-circuit test is inextricably bound up with the method of presenting and interpreting the results. In this connection I am indebted to Mr. Rowson for his comments on the use of the mode. The "number of meters/percentage accuracy" curve does, in practice, have a well-defined peak, and Mr. Rowson supports the use of the mode when this is the case, but I cannot agree that under these circumstances the arithmetic mean is equally suitable. For instance, if in a batch of 100 meters one was registering only 50 % of true accuracy, the arithmetic mean would be affected by 0·5 %, but the mode would not be affected at all. It would appear to be an advantage that the final result should not be affected by meters showing a wide divergence from true accuracy, as this is generally due to dirt or some cause

not typical of the meter. It is desirable, however, that the result should give an indication of the spread of the curve, and it would probably be advantageous to give both the mode and the mean-square deviation from zero error.

The definition of the mode is variously given as the most frequent size of item, the position of greatest density, and the position of the maximum ordinate in a smoothed histogram. A method of determining the mode is given in "Elements of Statistical Analysis" by W. I. King.

Paint spraying of meters.

I advocate the spraying of meter cases, as in practice it gives a better finish than hand painting and is much faster. The difficulties are the adequate cleaning of the case before spraying, and shielding of glasses, nameplates, coin chutes, etc., during spraying.

The case can be easily cleaned on a wire buff and the masking problem is solved by using metal masks for each part to be shielded, joined together with metal straps, so that the mask is fitted complete in one operation. Using this method one man can paint approximately 200 meters per day.

No difficulty is experienced with paint getting into the interior of the meter, and even the cover edges are adequately cleaned and painted.

Repairing of meters on test benches.

The repair of meters on the test benches is advocated not because a better job is obtained than when they are repaired on a separate repair bench, but because it saves disconnnecting and reconnecting the meter after off-circuit test. There is no reason, however, why the repair should not be carried out quite adequately without disconnecting the meter. As soon as the off-circuit test is complete, all top and bottom bearings are at once removed from all meters (where they are removable) and replaced by new bearings. The removed bearings are then examined by a mechanic using a microscope, the faulty ones are rejected, and the good ones are put into trays ready for inserting in the next batch of meters. Provided the meters are more or less standardized as to make and type, there is no reason why counters, coin mechanisms, and fixed-charge mechanisms, should not be dealt with in the same way. By this means there would be no need to disconnect the meter from the test bench; the bench would be occupied by repairs for the shortest possible time, and full advantage would be taken of specialists overhauling the mechanisms at a separate bench.

Mr. Richards advocates repairing meters as though they were watches, and Mr. Lees outlines a method which would undoubtedly meet with his approval. Unfortunately, neither of these speakers refers to costs.

By meticulous overhaul and repair it is possible to make the meter better looking than when it was new, and probably increase its performance on light loads to a slight extent. At much cost, friction is reduced, and then the low-load adjustment is moved to bring the meter back to its original curve. It probably gives the meter repairer a well-merited feeling of having done a good job, but it brings no extra revenue into the undertaking and does not increase the consumer's insurance against overcharge. After being in service for 6 months, the meter will have lost its pristine finish and be indistinguishable from a meter which has been only adequately repaired.

As Mr. Richards states, there are certain parts, such as the bearings of the rotor, which must receive very close scrutiny, but there are other parts which, however well polished, do not materially affect the accuracy of the meter.

However careful one is to clean and repair meters away from the test bench, there is always the risk of dirt getting into the magnet gaps before or during tests. These small pieces of dirt do not usually come from outside the meter, but have been lodged in a corner or jammed between the laminations of the electromagnets. Compared with this risk, the chance of dirt entering one meter when removed from the interior of another is negligible. Moreover, before finally passing the meter over for test it must always be very carefully examined for dirt. No trouble due to this cause has been experienced in the repair and testing of tens of thousands of meters, when the repair is carried out on the test bench.

Number of meters in batches.

In reply to Dr. Stritzl, it is very difficult to lay down the minimum number of meters which have to be dealt with for the economical operation of the proposed system of testing. From a consideration of running costs only, the system would be economical for a very small number of meters. The capacity of the benches would have to be reduced, but the number of benches would have to be sufficient to keep the staff always occupied. With only a small number of meters per bench, provision would have to be made for supplying low-voltage current. The capital outlay involved for space and control apparatus would, however, provide a minimum limit for the number of meters handled. The minimum is probably 500 meters per week.

Mr. Howarth's point regarding the number of meters dealt with in one batch is bound up with the total number of meters handled, the different varieties included in the total, the length of tests involved, and the number of benches provided. These are in themselves governed by the relative importance of standing and running charges.

The economical bench capacity depends entirely on local circumstances.

Single-phase test benches.

Mr. Howarth raises several points in connection with the single-phase test benches.

No provision is made for voltage variation on the individual single-phase test benches, as they are designed for use on one voltage only.

The method of obtaining lagging power factor by means of the voltage vectors does give 400 volts between current and pressure coils of the meter. In practice this has caused no trouble, but it would probably be better to avoid this by using a 1/1 potential transformer.

The potential-circuit tapping-key is used only when calibrating. It is closed for the period of 1 hour before the dial tests are started.

Fortunately for the meter industry, the Commissioners'

examiners are adopting a more common-sense interpretation of the Regulations than Mr. Page would evidently wish for. He seems to have overlooked the fact that method A does not necessitate the holding of either voltage or current at an exact value, and the meter accuracy is not materially affected by a slight variation from the exact load laid down by the Commissioners. It is one of the advantages of method A that the expensive apparatus advocated by Mr. Page is not required and would in no way add to the accuracy of the test. I made no attempt in the paper to minimize the power consumption for test purposes. This can be presented in no other way for comparative purposes than as units per meter tested, in the same way as other costs given in the paper. It is obvious that the electricity cost is negligible in comparison with other costs.

The benches equipped with 10/50-ampere transformers certainly will not test 100-ampere meters. They were not intended to, as there were no 100-ampere meters to test in the undertaking in question, all meters above the 50-ampere size being transformer-operated.

Mr. Fawssett and Mr. Page advocate the use of a range-change switch coupled to the load control, rather than a relay in the secondary circuit of the precision current transformer. The relay, however, is superior, as it protects the substandard meter under all conditions, including that of faulty load-control apparatus. The burden of the relay is 0·5 VA, so that it does not add appreciably to the existing burden of 2·5 VA on the 7·5 VA current transformer.

The plug connections in the voltage circuits referred to by Mr. Carr are substantial 5-ampere plugs, connected so that any possible drop in voltage across the contacts will affect both the substandard meters and the meters under test equally.

The ratio and phase-angle errors of the 10/50-ampere transformer are 0·35 % and 12 minutes at 66 % of full load, and 0·4 % and 19 minutes at 25 % of full load.

Polyphase test bench.

Mr. Howarth and Mr. Page draw attention to the arrangements shown in Fig. 2 for the testing of 2-element 4-wire meters.

In this diagram the common point of the voltage-transformer secondaries is joined to the common point of the current circuit, i.e. the system neutral. When testing 2-element 4-wire meters, the voltage in each phase is set on the phase voltmeter by means of the voltage regulator, so that it does provide the condition laid down by Mr. Howarth.

If, however, the voltages are purposely unbalanced, the inaccuracy of meters calibrated on the bench at 0·5 power factor (leading or lagging) will be the same percentage as the amount of voltage out-of-balance. This is a very serious criticism of this method of measurement, for while the conditions may be controlled in the test room, very appreciable error in registration may occur when a meter is fixed out on the network, and Mr. Page's remarks regarding these meters are very much to the point.

Mr. Ockenden raises a very controversial point about the relative merits of 1-amp. and 5-amp. rotating substandards. He does, however, appear to be under some misapprehension when he compares a 1-amp. rotating substandard with a 5-amp. substandard operating on a 0·25/5 current transformer. For correct comparison, the ratio of this transformer should be 1/5 amp.

To comply with the Commissioners' requirements in testing 2·5-amp. meters, it is necessary to have either a 0·5-amp. meter operating on a multi-range current transformer with 0·5-amp. secondary, or a 5-amp. meter operating on a multi-range current transformer with 5-amp. secondary and lowest range 0·5/5 amp.

Provided that all ranges in both instances are obtained by using the current transformer, the same voltage would be necessary in each instance for energizing the current-transformer primary. This could be avoided in the case of the 0·5-amp. meter by cutting out the current transformer for the 0·5-amp. range, but as this entails switching the current-transformer secondary connections it is a practice to be deprecated.

If the current transformer and meter are considered as a unit, there is therefore nothing to choose between the two methods. But to meet the Commissioners' requirements the 5-amp. meter would have to be tested down to a load of 0·25 amp. (5 % full load) and the 0·5-amp. meter down to a load of 0·05 amp. (10 % full load). The difficulty of the latter measurement is apparent.

It is a convenience if all portable instruments of the same type can be used on any current transformer which may be available, or in series with an integrating meter on a consumer's premises. As metering current transformers are standardized with 5-amp. secondary, it is necessary, in order to get this interchangeability, that all current transformers used in the test room should also have 5-amp. secondary windings. This has the additional advantage that all current transformers can quite easily be checked on the usual precision current-transformer testing-sets.

I have had no difficulty in purchasing step-up multi-range current transformers with the accuracy essential to precision measurements. The balance of argument would appear to be in favour of 5-amp. instruments.

The question of accidental open-circuiting of precision current transformers is one which must receive grave attention from all meter engineers, as there may be a very serious risk of fatal consequences. I am rather afraid of automatic short-circuiting devices, as these may, through failure to operate correctly, disturb the accuracy of measurement. The problem has been tackled in the benches shown in Figs. 1 and 2, by doing all range-changing on the primary side of the current transformer, so that all connections on the secondary side are solid and made so substantial, by means of sweating or lugs, that there is practically no danger of open circuit. Danger due to deliberate removal of connections cannot be avoided, whatever safety devices are incorporated.

The two types of test bench shown in Figs. 1 and 2 are fitted with a green indicating-lamp which glows when the bench is dead. Should the lamp fail, the bench is treated as alive. General instructions are given that no alteration may be made to connections on the bench, unless the green indicating-lamp is alight.

Laboratory equipment and testing.

Mr. Golds describes some very interesting experiments which confirm the accuracy of the method which he

describes for the testing of rotating substandard meters directly against a wattmeter and standard pendulum. This method has been in use in some test rooms for many years, and long experience has shown it to be extremely reliable and accurate. Mr. Golds has done good service by supporting this experience by laboratory tests.

I did not advocate an oscillograph for the purpose of detecting the 3 % deviation allowed by the Electricity Commissioners, but rather as a means of acquainting the testing engineer with the wave-forms he actually has to meter. Whether or not it can also be used to check the 3 % deviation would depend upon the type of oscillograph purchased.

Records and statistical analysis.

Mr. Moore, in concert with other speakers, says that statistical records and analysis can be carried too far. This is undoubtedly true, but has for corollary that they also can be carried not far enough. The difficulty is to define the state of perfection between these two extremes. In my opinion many undertakings do not collect enough statistics, but of the number who do, only a very small percentage abstract from them the useful information available.

Mr. Howarth criticizes the collection of statistics on the grounds that the information collected must necessarily relate to meters already on circuit and cannot be applied to meters not yet purchased. This is true of all experience and, if strictly applied, would mean that an experienced meter engineer's opinion regarding a new meter is of no more value than that of a person with no experience. Neither of them has any experience of the untried product, but it will be generally admitted that the opinion of the experienced man, based entirely on the performance of meters already purchased and on circuit, is more valuable than that of the inexperienced man. The value of his past experience would be greatly enhanced if his judgment were based on collected data carefully analysed, so that he did not entirely rely on these most deceptive things, memory and impressions.

This analysis has a definite monetary value greater than its cost. For instance, assuming that the cost of removing, repairing, and testing a meter to be 10s., if by statistical analysis such as that in Fig. 3 it is shown to be possible to extend the time of periodic change from 5 to 7 years, the saving on 10 000 meters would be £300 per annum. Many such savings are possible.

It has been suggested that, in order to obtain a comparison between different makes of the same type of meter, it is necessary to compare meters which have been fixed under identical conditions, for the same length of time, and of similar consumption. The work involved would, of course, prohibit any analysis of this nature, but the need for it is more apparent than real. There are cases where meters are fixed in coal cellars, damp cupboards, or other noisome places, and there are also cases of meters being overloaded or registering nothing at all; but these are the exceptions, and on the whole there is a remarkable similarity of running conditions for meters of the same size and type. The cases of bad location provide an instance of an impression being given (that the condition is prevalent) which would not be supported by statistical fact.

In reply to Mr. Hill, the following procedure has proved helpful in the matter of ensuring that no meter is fixed on a consumer's premises unless it is certified. The meter is sealed with the Commissioners' seal before being submitted to the examiner. Once it has been certified, a small red label is attached to the meter, and only meters so marked can be fixed on a consumer's premises. This system has the advantage that it avoids handling meters from a rack where they await certification, to one for certified meters only.

Reference back from the meter number to the test sheet is obtained by entering the test-sheet number on the meter-record card.

General.

Various speakers regret that the paper does not cover more ground and go into greater detail. It was hoped that the paper would be regarded as one dealing with general principles rather than with detailed procedure, the only detail included being that necessary to show that the methods advocated are workable.

It was also felt that a paper of this nature is not the place to criticize the requirements of the Commissioners under the Electricity Supply (Meters) Act, 1936, as such criticisms could not be replied to frankly by the Commissioners in the discussion.

I should, in conclusion, like to thank the many speakers who have taken part in the discussion for the very helpful ideas and criticisms which they have brought forward.

A RESONANCE BRIDGE FOR USE AT FREQUENCIES UP TO 10 MEGACYCLES PER SECOND

By Professor C. L. FORTESCUE, O.B.E., M.A., Member, and G. MOLE, Ph.D., B.Sc.

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SUMMARY

This paper describes a form of alternating-current resonance bridge suitable for measuring circuit resistances up to 30 ohms at frequencies up to 0·5 megacycle per sec. and up to 10 ohms at frequencies up to 10 megacycles per sec. The complete theory of the bridge and analysis of the errors is given, together with an account of a series of special check measurements designed to reveal the accuracy actually obtainable. The limit of error appears to be in the neighbourhood of 0·01 ohm for resistances up to 10 ohms at frequencies up to 10 megacycles per sec.

CONTENTS

(1) PRINCIPLES

The principle of the resonance bridge, which is well known, is shown in Fig. 1.

Three of the arms of the bridge—R_1, R_2, and R_4—are resistances. The other arm—C, L, R, and R_3—which contains the circuit under test, is tuned to resonance and so behaves also as a pure resistance. The bridge is thus entirely resistive and the conditions of balance are:—

$$LC\omega^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

$$R_1R_4 = R_2(R_3 + R) \quad . \quad . \quad . \quad . \quad (1b)$$

(2) REARRANGEMENT FOR USE AT HIGH FREQUENCY

At high frequencies the above conditions are modified by the presence of residual capacitances and inductances, and by the difficulty of constructing satisfactory variable resistances. In the present bridge the effects of residuals have been reduced by making the resistance arms in the form of fine wires mounted axially in screening tubes, and the difficulty with respect to the variable resistance is overcome by the use of a screened straight wire and sliding contact as shown in Figs. 2, 3, and 4. A Wagner earth is used which brings the sliding contact f to the potential of the screen. Neither its capacitance to earth nor the resistance of the contact affects the results under these conditions.

The ratio arms R_1 and R_2 are made in the form of a single wire mounted in a screening tube, with a soldered connection to the exact mid-point at b.

Still neglecting residuals, the conditions of balance become:—

$$LC\omega^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

$$R = R_4 - R_3 = 2\rho s \quad . \quad . \quad (2b)$$

where ρ is the resistivity of the slide-wire and s is the

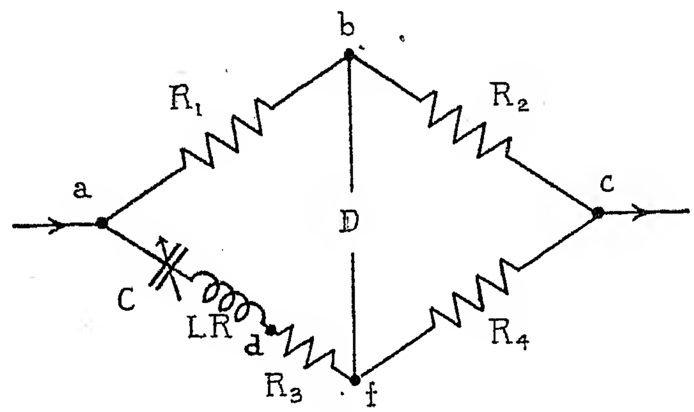

Fig. 1

distance of the contact from the mid-point of the slide-wire. The maximum resistance which can be measured is thus equal to the slide-wire resistance, and is in this case approximately 10 ohms. The range of resistance measurement with this bridge can be extended to 30 ohms at frequencies below 0·5 Mc./sec. by inserting an extra length of wire in the arm fc. This operation is not practicable at higher frequencies owing to the terminal capacitances at intermediate points in the arm.

(3) CONSTRUCTIONAL DETAILS

A complete circuit diagram of the bridge, Wagner earth, and circuit under test, is given in Fig. 2. A diagrammatic plan showing the actual construction is given in Fig. 3.

The apparatus consists of three cylindrical brass tubes 4 cm. diameter and 65–70 cm. long, and a rectangular copper box 80 cm. long and 9 cm. × 6 cm. cross-section. There are also smaller copper boxes at the ends, the whole

being soldered together to form the screening system of the bridge. The points a, b, c, d, f, on the bridge are exposed terminals, and the point e of Fig. 2 is the screen itself. The terminals are insulated with mycalex and have earth-capacitances of $4 \cdot 5$ $\mu\mu$F each.

The ratio arms ab and bc consist of a single length of No. 36 S.W.G. eureka wire mounted axially in the outer screening tube. The extra resistance used for extending the range of the bridge at low frequencies consists of two lengths of No. 36 S.W.G. eureka wire mounted in the two inner screening tubes. The ends of these wires are connected in the small copper box remote from c. The small copper box at the end c houses a system of three plug contacts by means of which the extra resistance can be either inserted in, or removed from, the bridge arm fc.

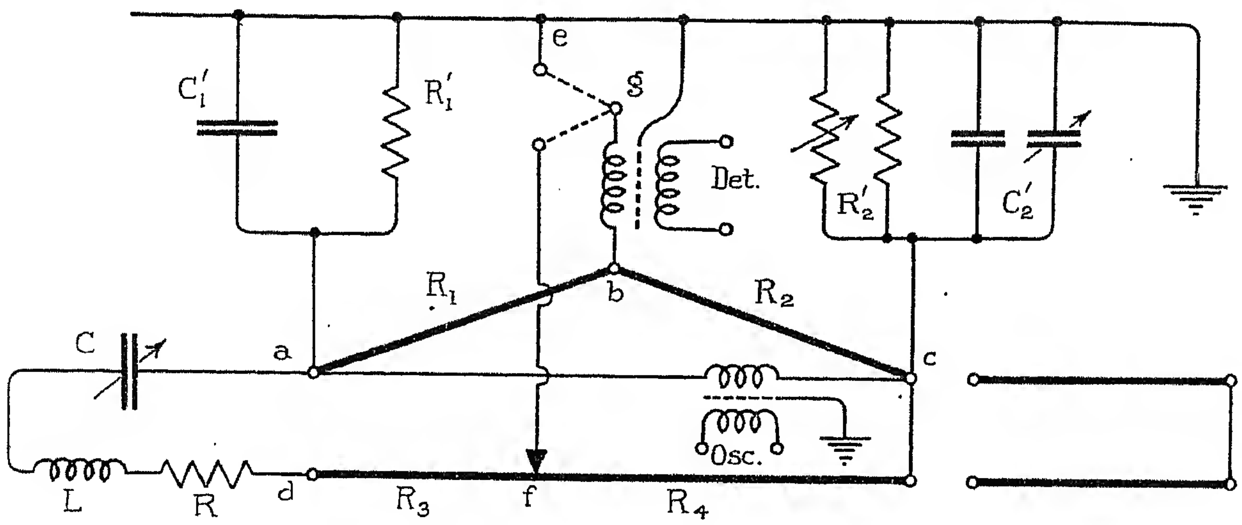

Fig. 2

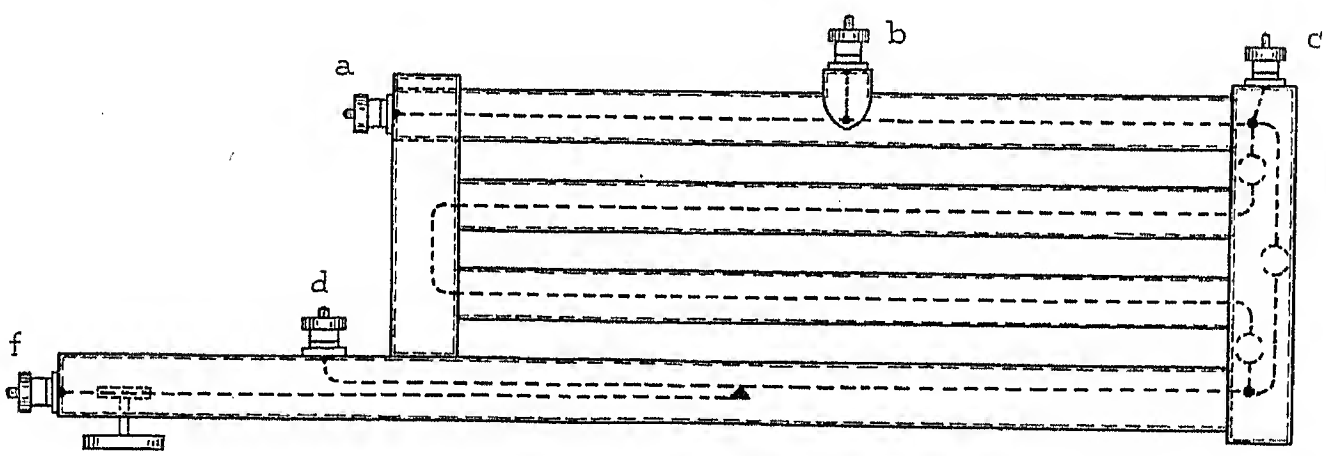

Fig. 3

The long copper box is divided longitudinally into three compartments as shown diagrammatically in Fig. 4. In the middle compartment is the slide-wire, consisting of No. 36 S.W.G. eureka wire equal in length to the ratio arms. In the upper and lower compartments is the variable-length connection between the terminal and the moving contact on the slide-wire f. A steel tape is arranged to run around the inside of the upper compartment, closing the longitudinal slot between the upper and middle compartments throughout the whole of its length except for a small insulating bush through which the connection to the contact passes. The steel tape runs over pulleys and is operated by an external handle, graduations on the tape being used to determine the position of the sliding contact. Glass rollers situated on

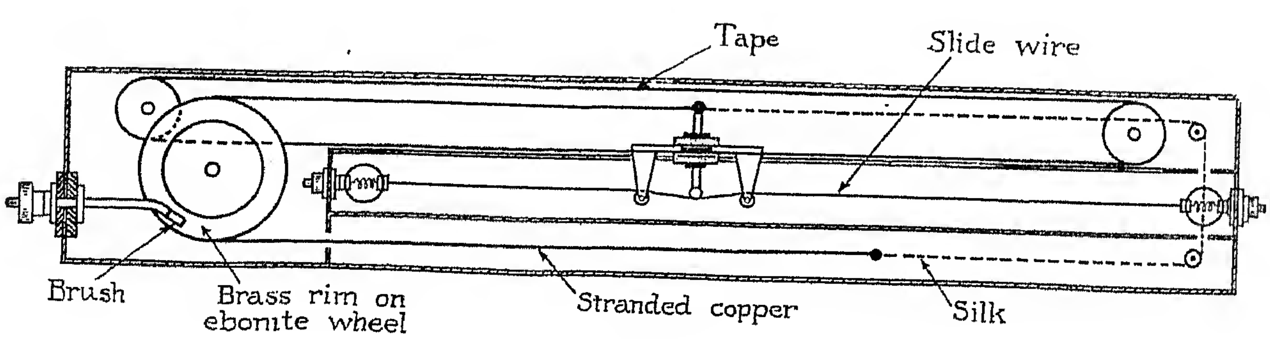

Fig. 4

either side of the contact wire and carried with it serve to bend the eureka wire slightly and so maintain the two wires in contact.

The eureka slide-wire is attached to its terminals in the manner shown in Fig. 4. The spring serves to maintain the wire taut under all conditions, and the ring of thin copper strip provides a low-impedance path for the current.

The Wagner earth system consists of fixed and variable condensers and resistances connected in parallel between the terminals a and c and the nearest points on the screen. The fixed condensers and resistances are arranged to plug in, and are required in values of 100–500 $\mu\mu$F and 1–20 Ω. Of these, the fixed condensers are mica-dielectric condensers of 2 cm. maximum dimensions and possess negligible self-inductance—an essential point since all possibilities of resonance must be avoided. The fixed resistances are carbon-bakelite composition resistances of similar dimensions, also possessing negligible self-inductance. The variable condenser is a small air condenser having a maximum capacitance of 100 $\mu\mu$F and completely screened. The variable resistance is a standard volume control possessing a metallic-film resistance element and having a maximum resistance of 200 Ω.

(4) ADDITIONAL APPARATUS

The additional apparatus required is an oscillator, a detector, and coupling transformers. The construction of the transformers is dependent upon the frequency range in use but is always so arranged that the primary and secondary impedances are approximately matched and the primary and secondary turns are electrostatically screened from each other. The connections between the bridge and the transformers are made with screened leads of equal length and cross-section.

The oscillator is of the ordinary push-pull type and is fed entirely by batteries. The oscillator, batteries, and transformer are enclosed within a copper box and form a unit which is completely screened from the rest of the apparatus. The copper box is itself enclosed within an aluminium screen.

The detector is of the simple heterodyne type and is fed from the mains. It consists of a push-pull, screen-grid, high-frequency amplifying stage; a heterodyne oscillator; a rectifier stage; and a stage of low-frequency amplification. The whole is enclosed within a partitioned aluminium screen.

It is important that there should be no direct coupling between the oscillator and the detector. The elimination of all such coupling is easily proved by disconnecting the bridge from the oscillator and detector leads, when no signal from the oscillator should be receivable. With the arrangement of multiple screening described above, no direct coupling is, in fact, detectable at any frequency up to 10 Mc./sec.

(5) WAGNER EARTH SYSTEM

The bridge is not connected directly to earth at any point, but when it is balanced the points b and f are exactly at earth potential. Earth capacitances at these points can therefore be neglected. This is essential, since the earth capacitance at f depends upon the adjustment of the slide-wire contact. The earth capacitances at a and c are in parallel with the Wagner-earth condensers C_1' and C_2', and form no part of the bridge circuit. The Wagner-earth system thus eliminates the effects of the earth capacitances at the points a, b, c, f.

The only earth capacitances remaining are the distributed capacitances of the wires and the capacitance at d. The maximum frequency at which the bridge is intended to be operated is 10 Mc./sec., corresponding to a minimum wavelength of 30 metres. The minimum half-wavelength, 15 m., is thus great in comparison with the length of either the ratio arms or the slide-wire, and consequently the distributed capacitances of the wires can be regarded as being concentrated at the ends, where they are merely parts of the earth capacitances at the points a, b, c, f, and d.

The effect of the total earth capacitance at the point d cannot be eliminated from the bridge. Therefore, either it must be made very small or a correction must be applied for it.

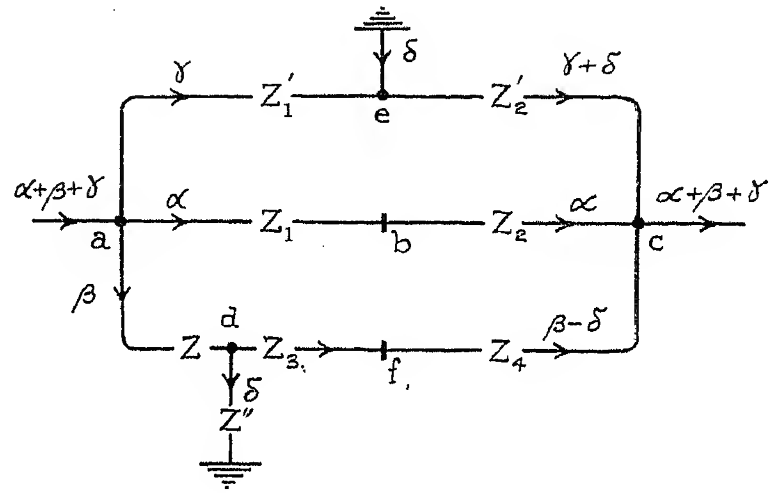

Fig. 5

(6) COMPLETE THEORY OF BRIDGE AND WAGNER EARTH

Fig. 5 is a complete circuit diagram of the bridge and Wagner earth, including the earth capacitance at the point d. The symbols Z_1, Z_2, Z_3, Z_4, Z_1', Z_2', Z'', Z represent the complex values of the impedances constituting the network, whilst α, β, γ, δ represent the complex values of the currents in the network.

A balance occurs when the points e, b, and f are at the same potential. Since the two ratio arms are made equal, $Z_2 = Z_1$. Therefore,

$$Z_1\alpha = Z_1'\gamma \qquad (3a)$$

$$Z_1\alpha = Z\beta + Z_3(\beta - \delta) \qquad (3b)$$

$$Z_1\alpha = Z\beta + Z''\delta \qquad (3c)$$

$$Z_1\alpha = Z_2'(\gamma + \delta) \qquad (3d)$$

$$Z_1\alpha = Z_4(\beta - \delta) \qquad (3e)$$

Eliminating Z_1, α, β, γ, and δ,

$$\frac{1}{Z_2'} - \frac{1}{Z_1'} = \frac{Z_3}{Z_4 Z''} \qquad (4a)$$

$$Z = \frac{Z_4 - Z_3}{1 + \dfrac{Z_3}{Z''}} \qquad (4b)$$

When separated into real and imaginary parts, equations (4*a*) and (4*b*) become:—

$$\frac{1}{R_2'}-\frac{1}{R_1'}=\frac{(R_3L_4-R_4L_3)C''\omega^2}{R_4^2+L_4^2\omega^2} \quad . . . . \quad (5a)$$

$$C_2'-C_1'=\frac{(R_3R_4-L_3L_4\omega^2)C''}{R_4^2+L_4^2\omega^2} \quad . . . . \quad (5b)$$

$$R=\frac{R_4-R_3+(R_4L_3-R_3L_4)C''\omega^2}{(1-L_3C''\omega^2)^2+R_3^2C''^2\omega^2} \quad . . . \quad (6a)$$

$$L\omega-\frac{1}{C\omega}=\frac{(L_4\omega-L_3\omega)(1-L_3C''\omega^2)-(R_4-R_3)R_3C''\omega}{(1-L_3C''\omega^2)^2+R_3^2C''^2\omega^2} \quad (6b)$$

It will be seen that equations (5*a*) and (5*b*) represent the conditions of balance for the Wagner earth, whilst equations (6*a*) and (6*b*) represent the conditions of balance for the bridge. The equations (5*a*) to (6*b*) are greatly simplified if it is permissible to assume that the inductance and resistance of the end connections are relatively small compared with those of the wires and that, in addition, the ratio of the resistance to the inductance of the end connections does not differ greatly from that of the wires. Under these conditions,

$$R_3L_4=R_4L_3$$

and

$$\frac{(R_4-R_3)R_3C''}{L_4-L_3}=\frac{R_3^2C''}{L_3}$$

Equations (5*a*), (5*b*), (6*a*), and (6*b*) therefore reduce to:—

$$R_1'=R_2' \quad . . . . \quad (7a)$$

$$C_2'-C_1'=\frac{(R_3R_4-L_3L_4\omega^2)C''}{R_4^2+L_4^2\omega^2} \quad . . . . . . \quad (7b)$$

$$R=\frac{R_4-R_3}{(1-L_3C''\omega^2)^2+R_3^2C''^2\omega^2} \quad . . . \quad (8a)$$

$$L\omega-\frac{1}{C\omega}=\frac{(L_4\omega-L_3\omega)\left(1-L_3C''\omega^2-\frac{R_3^2C''}{L_3}\right)}{(1-L_3C''\omega^2)^2+R_3^2C''^2\omega^2} . \quad (8b)$$

In the case of the present bridge with a value of C'' of 40 $\mu\mu$F, the maximum values of the terms $R_3^2C''^2\omega^2$ and R_3^2C''/L_3 are respectively 0·00015 and 0·0003, and may be neglected in comparison with unity. Equations (8*a*) and (8*b*) thus become:—

$$R=\frac{R_4-R_3}{(1-L_3C''\omega^2)^2} \quad . . . \quad (9a)$$

$$L\omega-\frac{1}{C\omega}=\frac{(L_4-L_3)\omega}{1-L_3C''\omega^2} \quad . . . \quad (9b)$$

The bridge balance is represented by equations (9*a*) and (9*b*) with a maximum error of 1 part in 2 000. Inspection of equations (7*a*) and (7*b*) shows that the adjustment of the Wagner earth is dependent upon the slide-wire adjustment.

(7) CALIBRATION

The bridge was calibrated with direct current by connecting a standard variable resistance between the terminals *a* and *d*.

(8) CORRECTIONS

For resistance measurements having an accuracy of the order of 2 %, it is possible to use directly the d.c. calibration of the bridge. When more accurate measurements are to be made, it is necessary to apply a correction for skin effect in the slide-wire. The values of the correction in the case of the present bridge are given in Table 1, where $R_{D.C.}$ is the test-circuit resistance as determined from the bridge balance and the d.c. calibration and R_F is the test-circuit resistance after correction for skin effect in the slide-wire.

Table 1

f (in Mc./sec.) =	0·70	1·30	2·00	3·00	5·00	7·50	10·00
$R_F/R_{D.C.}$ =	$1{\cdot}000_1$	$1{\cdot}000_2$	$1{\cdot}000_4$	$1{\cdot}001_0$	$1{\cdot}002_9$	$1{\cdot}007_3$	$1{\cdot}013_2$

Where the effect of the capacitance C'' is appreciable, it is necessary to use the relations (9*a*) and (9*b*). These may be rewritten:—

$$R_E=R=\frac{R_F}{(1-L_3C''\omega^2)^2} \quad . . \quad (10a)$$

$$L\omega-\frac{1}{C\omega}=\frac{\omega\mu R_{D.C.}}{1-L_3C''\omega^2} \quad . . . \quad (10b)$$

where μ represents the ratio of inductance to d.c. resistance in the slide-wire. For the present bridge the value of μ is 0·068 μH per ohm, and the value of L_3 is given (in μH) by

$$L_3=0{\cdot}354-0{\cdot}034R_{D.C.}$$

(9) HIGH-FREQUENCY OPERATION

The circuit under test should be connected across the terminals *a* and *d* on the bridge in such a way that the part of the circuit possessing the greatest earth capacitance is connected to the point *a*. The earth capacitance at *d* should be as low as possible.

The bridge and Wagner earth require four adjustments for balancing. They are (i) the adjustment of the Wagner-earth variable resistance R_2', (ii) the adjustment of the Wagner-earth variable capacitance C_2', (iii) the adjustment of the slide-wire contact, and (iv) the adjustment of the variable reactance in the test circuit. Of these, (i) is independent, but (ii), (iii), and (iv) are interdependent. Adjustment (ii) has, however, only a small effect on (iii) and (iv). The final adjustment is indicated by a minimum of sound in the telephone, but if the

adjustment of the slide-wire contact is not near its correct value then the reactance adjustment (iv) should be to a maximum instead of a minimum, since it is then a form of resonance adjustment. It is possible to obtain a perfect balance of both bridge and Wagner earth over the whole range of frequency for which they are intended to be used, i.e. from 0 to 10 Mc./sec.

(10) HIGH-FREQUENCY TEST CIRCUIT

A circuit employed for testing the accuracy of the bridge over the frequency range 1–10 Mc./sec. is shown in Fig. 6. It consisted of a standard, variable, air condenser, a doubly-screened coil, and a doubly-screened resistance unit. The air condenser was one of two, possessing maximum capacitances of 1 200 $\mu\mu$F and 200 $\mu\mu$F and having very low power factors. The coils were available in values ranging from 0·5 μH to 50 μH.

The resistance took the form of a three-terminal, screened, plug-in holder arranged to take one of two resistance units. These two units consisted of equal 15·5-cm. lengths of No. 40 S.W.G. copper and eureka wires of uniform and equal diameters, mounted in similar brass screening tubes. The two units thus possessed equal self-inductance and self-capacitance but differed in resistance. Substitution of one unit for the other, therefore, would produce a resistance-change in the test circuit

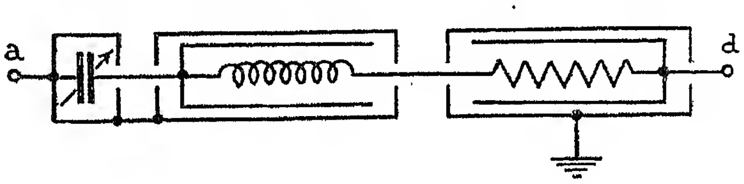

Fig. 6

but would not in itself change the reactance of the circuit. The readjustment of the slide-wire contact necessitated by the resistance-change would, however, require to be balanced by a capacitance-change in the test condenser. In order to ensure that this capacitance-change would not have associated with it an extra, small, resistance-change, it was necessary that the power factors of both the condenser and the capacitance between the inner and outer coil screens should be low.

The direct-current resistances of the units, $R_{d.c.}$, were measured with the bridge itself, using a current of only 5 mA in order to avoid thermal resistance-change in the copper unit. A current of the same order of magnitude was employed in the high-frequency tests.

In order to determine the effective resistances, R_e, of the units it was necessary to apply corrections for (i) skin effect (giving R_f) and (ii) the effect of the self-inductance l and self-capacitance c of the units. The latter correction was given by

$$R_e = \frac{R_f}{(1 - lc\omega^2)^2}$$

Other residuals in the circuit were treated as follows: The capacitance between the inner and outer resistance-unit screens merely added to the existing earth capacitance C'' at d and could be taken into account by using the exact bridge-balance relations (10a) and (10b). The connection between the coil and the resistance unit was made so short that any residual associated with it could be neglected. The capacitance between the inner and outer coil screens merely added to the condenser capacitance. The earth capacitances of the outer coil screen and of the condenser screen formed part of the Wagner earth circuit and so did not affect the bridge.

(11) RESULTS OF HIGH-FREQUENCY TESTS

The bridge was tested over a frequency range of 1–10 Mc./sec. using the test circuit described above. The effective high-frequency resistance of the test circuit was measured with the copper resistance unit and again with the eureka resistance unit. The difference gave the difference between the effective high-frequency resistances

Table 2

Frequency	Test coil	Resistance difference (Eureka — Cu)			Percentage error
		Test resistance value	Bridge value	Error	
Mc./sec.		Ω	Ω	Ω	
1·30	A	6·30$_7$	6·31$_9$	+ 0·01$_2$	+ 0·2
	a	6·30$_7$	6·27$_2$	− 0·03$_5$	− 0·5
	a$_2$	6·30$_7$	6·29$_8$	− 0·00$_9$	− 0·1
2·00	a	6·30$_3$	6·30$_2$	− 0·00$_1$	− 0·0
	a$_2$	6·30$_3$	6·28$_0$	− 0·02$_3$	− 0·4
3·00	a$_2$	6·29$_3$	6·28$_7$	− 0·00$_6$	− 0·1
	7t	6·29$_3$	6·28$_8$	− 0·00$_5$	− 0·1
5·00	7t	6·27$_1$	6·23$_9$	− 0·03$_2$	− 0·5
	4t	6·27$_1$	6·27$_9$	+ 0·00$_8$	+ 0·1
7·50	7t	6·25$_3$	6·24$_9$	− 0·00$_4$	− 0·1
	4t	6·25$_3$	6·27$_6$	+ 0·02$_3$	+ 0·4
	2t	6·25$_3$	6·27$_3$	+ 0·02$_0$	+ 0·3
10·00	4t	6·25$_5$	6·22$_7$	− 0·02$_8$	− 0·4
	2t	6·25$_5$	6·27$_6$	+ 0·02$_1$	+ 0·3

of the two units and could be compared with the known value of this difference as determined by direct-current measurement and correction. The results of the tests are given in Table 2.

It will be seen that the mean error in the measurement of a resistance of 6·3Ω is 0·01$_6$Ω, or 0·25 %. Since this represents the sum of the errors in two measurements, it can be said that the bridge is capable of measuring resistances of 0–10Ω over the frequency range 1–10 Mc./sec. with a probable error of ± 0·01Ω. It appears from Table 2 that the errors are randomly distributed over the frequency range. The accuracy of the bridge does not, therefore, appear to diminish with increasing frequency.

(12) USE OF BRIDGE

The bridge can be used for obtaining accurate comparisons of the resistance and reactance of any circuit at frequencies up to 10 Mc./sec., providing (i) the equivalent

series resistance does not exceed 10Ω (30Ω for frequencies below 0·5 Mc./sec.), (ii) the reactance is finely adjustable to resonance, and (iii) the circuit does not possess excessive capacitance to earth at points other than its terminals. Where there is choice in the arrangement of screens it is possible completely to eliminate earth capacitance of internal parts of the test circuit, as in the circuit of Fig. 6.

A useful test circuit for measurement of the reactance and resistance of screened coils is shown in Fig. 7. The capacitance at the point d can be made sufficiently small to render correction for it unnecessary. If a low-power-

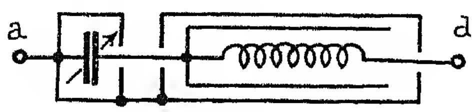

Fig. 7

factor condenser is used, the equivalent series resistance of the coil is obtained directly from the slide-wire calibration with a limit of error of 1 % and, after correction for skin effect only, with greater accuracy. The reactance is given by

$$\frac{1}{C\omega} + \omega\mu R_{D.C.}$$

where C is the condenser capacitance. It should be observed that only when one terminal of the coil is connected to the screen are the effective values of reactance and resistance independent of the circuit in which the coil is connected.

The bridge is, in general, found to be more sensitive than the existing resonance methods for measurement of reactance and resistance over the 1–10 Mc./sec. frequency range.

(13) FURTHER DEVELOPMENT

There is at present under construction a bridge similar in principle to the above but of smaller dimensions, which is intended to cover the frequency range 10–100 Mc./sec.

(14) ACKNOWLEDGMENTS

Much of the preliminary work on this bridge was carried out by postgraduate students of the City and Guilds College, South Kensington, notably Dr. Z. U. Ahmad and Mr. R. P. Glover. This work prepared the way for later developments. The completion of the work was rendered possible by the generous grants for research made to the College by the Worshipful Company of Clothworkers.

(15) BIBLIOGRAPHY

Details of previous forms of radio-frequency bridge will be found in the following papers:—

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(3) W. J. Shackleton: "A Shielded Bridge for Inductive Impedance Measurements," *Bell System Technical Journal*, 1927, vol. 6, p. 142.
(4) J. G. Ferguson: "Shielding in High-Frequency Measurements," *ibid.*, 1929, vol. 8, p. 560.

DISCUSSION BEFORE THE WIRELESS SECTION, 2ND FEBRUARY, 1938

Dr. L. Hartshorn: The sensitivity and perfection of balance of the bridge can, in these days of amplifiers, and efficient screening and earthing, be taken for granted. The practical value of the new bridge will therefore depend on its overall accuracy, convenience in use, and flexibility, i.e. the ease with which it may be adapted to deal with jobs of various kinds. It would be of great value if the authors could give some idea as to how the bridge compares with alternative methods in these respects. The estimated limit of error of 1 in 1 000 is probably also the upper limit of accuracy obtainable by the resonance method. The fact that the reactance is tuned for a maximum of sound in the initial stages, and a minimum in the final stages, suggests that the adjustments might at times be less straightforward than those of untuned bridges, but it may be that the apparent ambiguity causes no practical inconvenience.

The resonance bridge was used some years ago at the N.P.L. at audio frequencies, but was discontinued for measurements on ordinary coils, owing to the fact that at resonance the junction of coil and condensers is at very high potential, and that therefore errors due to any earth-capacitance currents at this point are apt to be unduly large. The Wagner earth only allows for capacitance currents at the corners of the bridge; the bridge readings are therefore a function of the earth capacitance at the junction in question, and are in consequence limited in their application to the special conditions imposed by the bridge network. The authors' scheme of connections shown in Fig. 6 is exactly that required to eliminate error due to this cause: the screens are so arranged that the junction has capacitance to the condenser screen-terminal but not to earth. I regard this feature as essential for accurate results. Does not the necessity for such conditions limit the application of the method somewhat severely? Measurements on unscreened coils would, I think, from my own experience, be subject to larger errors if made by this method. Nevertheless, it is of the utmost importance that the full possibilities of such methods should be thoroughly explored, and in showing that the method is capable of an accuracy within 0·1 % at 10 Mc./sec. under suitable conditions the authors' investigation is a valuable piece of work.

Mr. T. Iorwerth Jones: It is interesting to recall that the earliest form of radio-frequency bridge, described in this country about 15 years ago by Mr. M. Hart, was also developed at the City and Guilds Engineering College. In some respects it resembled the bridge described in the present paper. Its arms consisted similarly of eureka wires, rather longer, of course, than those in the authors' apparatus. A movable contact was realized by threading the wire through a small cube containing mercury, the holes being so small that the mercury did not escape. There was no screening. The full implications of the pioneer work of G. A. Campbell, and its

later development at the hands of Shackleton and Ferguson, of the Bell Telephone Laboratories, were realized subsequently. When we came to design a radio-frequency bridge at the N.P.L., in adapting a bridge to radio frequencies we introduced a great deal of screening; we were compelled to do so, because we were aiming at the measurement in the first place of very, very small phase angles associated with the effective resistances of condensers, phase angles which can frequently be as low as 6 sec. of arc at 1 Mc./sec. The bridge was also intended for measurements on dielectrics. In those measurements the apparatus was provided with two electrodes and a guard-ring, and the potential of one of those electrodes had to be maintained accurately at the potential of the guard-ring, otherwise a different result would be obtained, depending upon the choice of the arm into which the apparatus was inserted. Screening and the elimination of induction into the detector circuit were the essential precautions which had to be observed.

The authors' bridge is essentially a bridge with low-impedance arms. It is assumed that it is not intended for the measurement of very small phase-angles. This allows of greater latitude in the matter of screening—at the upper reaches of the frequency range this becomes imperative if the bridge is to remain workable, otherwise the earth admittances would exceed the measured admittances and complicate the result. There is a definite limit to the accumulation of earth capacitances above 1 Mc./sec. The authors' bridge appears, in general, to be admirable for the measurement of screened inductances and for the adjustment to resonance at a definite frequency of screened composite units intended for filter circuits, and as a means of deriving a knowledge of the resistance of such components. There is one feature, however, on which one is not too happy. The tapping on the variable resistance carries a detector point which moves a considerable distance along the wire between the two balances obtained with the apparatus under test included in, and removed from, the bridge arm respectively. This movement may modify the mutual induction between the source circuit and the detector circuit which may almost inevitably exist to a small extent. It is difficult to estimate this effect from a cursory glance at the assemblage.

A few years ago, in the course of a review* of high-frequency bridge networks, I had occasion to comment upon the absence of satisfactory standards of resistance for work at high frequency. The authors' bridge embodies standard resistances both of the fixed and of the variable types which are admirably screened and compact.

Mr. E. B. Moullin: The authors use a battery-driven generator and mains-operated receiver, or vice versa. I presume they fear to use two mains-driven pieces of apparatus lest a signal should pass from one to the other through the a.c. system. I should like to know whether they think it is beyond their ingenuity to arrange for both units to have a.c. drive.

I notice that the authors use mycalex for terminal bushings; had they any reason for using it in preference to, say, trolitol, which I myself prefer?

It is a little difficult to assess the order of importance of C'' from the two bridge-balance conditions, equations (10*a*) and (10*b*). Its action is that the equivalent of inserted resistance in Fig. 5 is shunted by a capacitance, so that its effective resistance is smaller than it ought to be; the difference is enhanced by the residual inductance of the arm. I feel that the effect of C'' is probably very small indeed, because L_3 can be made very small. Why was no test made by connecting a variable capacitance to earth from the danger point d, and examining the inaccuracy produced?

It is stated in Section (10) that the inductances of units of copper wire and eureka wire are the same. I maintain there is a certain range of frequency in which the two values will not be the same, because the inductance due to the internal field is a function of frequency and is not a negligible fraction of the total inductance. I suggest that the inductance for steady currents would be about 10 % more than the limiting final value. The rates of approach to that lower value would be different for the copper and the eureka, having two different penetrations. As I presume that the term L_3 in equation (10*a*) is negligible anyhow, this discrepancy does not much matter.

It would be valuable if other speakers in the discussion would give their views as to the relative merits of the use of a bridge and of straightforward resonance methods. I hope it is still reasonable to go on using resonance rather than bridge methods, and I gather that Dr. Hartshorn thinks likewise. What do we gain by using a bridge method? Essentially that we cut out any indicating instrument the law of whose scale we have to rely on. We throw all the responsibility on to a standard resistance or condenser: provided these remain constant then obviously the bridge method gives a much higher degree of possible accuracy of reading than the resonance method. My experience of resonance methods has not revealed a lack of accuracy of reading, desirable as it may be to have the further extended accuracy of reading which the authors' bridge must undoubtedly give. There is, however, one point which is worth bearing in mind. So far as my experience goes, the high-frequency resistance of a circuit is not constant from day to day to the extent of 2 parts in 1 000. It is easy to make a coil which has a power factor of 0·3 %, and the operation becomes successively easier as one goes to higher and higher frequencies. That being so, the power factor of the condenser becomes an appreciable fraction, of the order of 10 %, of the whole. I think that in ordinary circumstances the power factor of condensers, with their bushings affected by conditions of weather, is slightly variable from day to day. It is certainly my opinion that there is not a greater day-to-day constancy than about 0·5 %, so that I think there is an upper limit to which it is useful to go for precision of comparison.

A further point which occurs to me is that the authors' bridge essentially measures resistance, whereas in general the quantity which is more important in high-frequency work is the power factor of the circuit.

Mr. Charles Holt Smith: I have throughout the last year been developing a bridge which is complementary to the authors'. The conditions which I had to fulfil were that it should be suitable for use in the field at Daventry for the purpose of measuring and adjusting short-wave transmitter aerials. It had therefore to be easily port-

* E.R.A. Report L/T 56, 1933.

able, and weatherproof. It had to operate over frequencies between 6 Mc./sec. and 24 Mc./sec. and to be suitable for measuring balanced impedances. Fortunately, a limit of error of the order of 5 % was considered ample. This bridge was duly constructed, and it served a very useful purpose throughout the past year in connection with the setting-up of the Daventry aerials.

The difficulties experienced by residual capacitance at the junction point of a standard resistance and condenser were avoided by connecting the standard resistance and condenser in parallel, so that the answer obtained for the unknown impedance was expressed as the equivalent parallel resistance and reactance. The reactance was measured by means of a double differential condenser. Differential condensers were employed in order that by transferring negative reactance into either the test arm or the standard arm of the bridge, positive or negative reactance could be measured, and two condensers were used in series to give a balanced system with the centre-point earthed. The resistance component of the impedance to be measured was determined on a carbon track varying with the resistance. The resistance used was a hand-calibrated Morgan–Stackpole 1 000-ohm resistance. The resistance track was of a form conforming to no previously known rule, having been designed in such a manner that the scale was open mainly in the region round about 600 ohms, at which value maximum accuracy was required. A further device which was incorporated permitted the whole of the range from zero to infinity shunt resistance to be included on a single dial. By connecting across the test terminals of the bridge a variable resistance, and by means of an initial bridge adjustment whereby this resistance was made equal to the maximum value of the variable resistance in the standard arm of the bridge, the external shunt resistance across the test arm under conditions of balance was given the value infinity; whereas when the standard resistance was turned down to zero the total resistance variation was from zero to infinity. The reactance variation was of the order of $\pm$ 70 $\mu\mu$F.

Dr. M. Reed: Have the authors been able to verify that the magnitude of the contact resistance which would be at f if the whole of the variable resistance was confined to R_4 is sufficient to justify the considerable complication caused by leaving d with an impedance to earth?

Although the use of cylindrical tubes does seem to give an ideal layout from the electrical point of view, it is interesting to consider whether equal results could not have been achieved by a more compact form of bridge. For example, have the authors investigated the possibility of (*a*) using for their ratio-arms balanced coils wound with twisted pair on a core of ferromagnetic material suitable for operation at high frequencies, (*b*) having a spool consisting of an Ayrton–Perry winding of eureka wire on a small card of, say, 1 in. square for the additional fixed resistances?

In connection with the formula for the reactance correction given in (10*b*), have the authors considered the possible inductance of the air condenser, and, if so, is its magnitude too small to be included in the correction term? Finally, since the errors given in Table 2 seem to be independent of frequency, what decides the limiting frequency at which the bridge can be operated?

Mr. N. Lea: I should be interested to learn whether the authors have made any assessment of the errors they would expect beyond the limit which they have imposed on the working frequency of their bridge, namely 10 Mc./sec.

A further point is that the figure of $4 \cdot 5$ $\mu\mu$F mentioned for the capacitance of terminals is a little higher than one would expect to be necessary. Have the authors tried to reduce this value?

I am not quite sure whether Mr. Moullin's remarks about an alternative method of measurement referred to the resonance method wherein one injects a known voltage into the circuit under test and then measures the voltage across the circuit. If so, I agree with him that it is possible to get all the discrimination which one needs with that arrangement, the limit of error being less than 1 in 1 000. Some time ago, I had occasion to carry out some radio-frequency loss tests on good-quality insulating oils, and I found that with quite reasonable precautions one could detect changes of the order of $0 \cdot 0001$ ohm in about 5 ohms.

Dr. Hartshorn has made a very strong point about the danger associated with the mid-point between the condenser and the inductance in the circuit to be measured. This is of even more importance in commercial work, where often we have to deal with quite large coils and condensers.

Dr. A. Rosen: The authors state that their bridge is to be regarded as suitable for reactance as well as resistance measurements; the variable condenser C is consequently an essential part, and more detailed information concerning it might be included in the paper, possibly in Section (4). In that case, the condition that the reactance of the measured circuit should be finely adjustable could be omitted from Section (12). On the other hand, I would suggest that the following limitations be added: (*a*) The measured circuit must not be earthed at any point. (*b*) It should be completely shielded, as shown in Fig. 7, preferably with an additional earthed screen to make the capacitance to earth constant. (*c*) The capacitance between the screens, which is thrown across the variable condenser C, should be low enough to permit the circuit being brought to resonance. (*d*) The dielectric between these screens should be of the highest quality, so that this capacitance has negligible series resistance.

Mr. H. Page (*communicated*): In making measurements on coils by means of an impedance bridge, it is desirable to connect the coil in the same way as that in which it is used in practice. In the case of a series-tuned circuit, for instance, the value of resistance in which we are interested is that obtained by measuring the series resonant impedance. In the case of a parallel-tuned circuit, however, the effective resistance of the coil can only be obtained by measuring the parallel resonant impedance; in this case the self-capacitance of the coil forms part of the tuning condenser and does not affect the resistance measurement. The effect of self-capacitance can, of course, be calculated, but the calculation is laborious and generally inaccurate.

The application of the series resonance bridge is limited, therefore, to coils of small inductance, in which the self-capacitance does not affect the resistance measurement. This excludes the majority of coils used in modern broadcast receivers.

The use of wire mounted axially in screening tubes for the ratio arms is interesting; in the types of bridge normally used for impedance measurements, these take the form of lumped elements, either the inductive type or Ayrton–Perry resistance windings. Two similar units give good equivalence of impedance up to 5 Mc., and possibly higher, but I am not aware of any tests which have been made to the same accuracy and over the same frequency-range as those of the authors. Their experience in this respect would be of interest.

Prof. C. L. Fortescue and **Dr. G. Mole** (*in reply*): Several speakers have raised the question of the nature of the measurements for which this bridge is designed. It was originally intended for the measurement of the equivalent series resistance of any series L—C—R circuit or of any combination of circuits that could be represented by L, C, and R in series at the particular frequency in use. It must be possible to adjust the equivalent reactance, and under the conditions of measurement no part of the circuit under test is actually earthed. Both ends of the circuit under test are, however, very nearly at earth potential, and any leakage from the high-potential point of the circuit will only be that occurring under normal operating conditions. Thus, contrary to the opinions expressed by one or two speakers, no error arises from this cause. It is only when attempting to prove the accuracy of the bridge, as described in Section (10) of the paper, that this leakage has to be reduced to a minimum or by some means maintained constant.

As a by-product, the bridge proved extremely convenient for the comparison of reactive components by the method of simple substitution.

The bridge is not adapted for the measurement of parallel L, C, R circuits, owing to the difficulty of obtaining high resistances of accurately known values and to the intention of keeping all the impedances of the bridge quite low. Thus inductances tuned wholly or nearly wholly by self-capacitance cannot be compared on this bridge. The simple form of bridge described by Mr. Smith illustrates this difficulty, for he claims a limit of error of only $\pm$ 5 %, whereas the bridge described in the paper has a proved limit of error approaching 0·1 %.

The screening of the test circuit has been mentioned. Screening is not necessary unless it is the normal operating condition. But if it is not provided the resistance and reactance will depend upon the immediate surroundings, and any re-arrangement will lead to a change of resistance which actually occurs and which is duly recorded by the bridge measurement.

The result given by the bridge is an effective resistance. The frequency is known, and if either L or C is known the power factor of the circuit as a whole can be found. The power factor of either the capacitance or the inductance alone cannot be found, but change of power factor due to change of components is easily observed.

The relative advantages of the bridge measurement and the resonance measurement is naturally the subject of several questions. Mr. Moullin really answers these questions, except that he does not mention the important fact that when the resonance method is used there will either be some uncertainty with regard to the losses or the additional reactance involved in the indicating instrument; or the complication of the Mallett–Blumlein method will be involved. The bridge gives the effective series resistance without these difficulties. It does not give a power factor, but in practice the effective resistance is usually the more important. The bridge measurement is probably slightly more accurate than the resonance measurement, the circumstances being similar.

Mr. Moullin mentions several other important points. It is quite possible that both receiver and oscillator could be operated from the mains, but this plan was not adopted, as it seemed unwise to run any risks in the course of the development of the bridge. The change of inductance of the copper and eureka wires is an important point where this substitution is employed. In the present instance the possible change of L is about 0·008 μH in a total inductance of the resistance wire of 0·18 μH, which is, in itself, only a part of the whole inductance of the circuit. The error arising from this cause is thus very small. With regard to the effects of C'', the tests of the bridge given in Section (10) involved capacitances much higher than those to be expected under normal conditions of working. Thus, if the corrections were satisfactory in those tests there is no reason to suppose that greater errors will arise when the capacitance C'' is much less. The material used for the terminal insulators is unimportant, owing to the low impedance of the bridge. Mr. Lea suggests that the terminal capacitance should be less than 4·5 $\mu\mu$F, and he may be interested to know that in the new bridge, designed for higher frequencies, this capacitance is reduced to little over 1·7 $\mu\mu$F.

The limitation of frequency with the original bridge arises from a variety of causes such as the high terminal capacitance mentioned by Mr. Lea, and the distance apart of the terminals to which the test circuit is connected. Primarily, however, the limitation arises from the fact that the series resistances of higher-frequency circuits are too low to be measured accurately on a 10-ohm slide wire of under 1 metre in length.

Two speakers have suggested the use of wound coils for the ratio arms. This is possible, but it is not so easy to ensure their equality under all conditions as in the case of the straight wire tapped at the centre, where a single resistance comparison ensures equality of reactance within the limits of constancy of the wire.

Mr. Jones asks whether variation of the position of the slide-wire contact causes a variation of the coupling with the receiver. The sliding contact is always at earth potential when the bridge is balanced, and it thus seems unlikely that any error can arise from this cause.

DISCUSSION ON "THE EFFECTS OF IMPULSE VOLTAGES ON TRANSFORMER WINDINGS"*

WESTERN CENTRE, AT CARDIFF, 10TH JANUARY, 1938

Mr. J. B. J. Higham: The value of the authors' cinema film showing the effect of impulse voltages on transformer windings would be increased if the amplitude of the constant impressed voltage were indicated at the side; alternatively it could be represented by a horizontal dotted line. One would then be able to gauge the magnitude of the voltage at all points in the winding very much more readily.

I am interested to learn that the use of Petersen coils may accentuate the effects which impulse voltages produce in transformer windings. It would appear that certain eventualities which are more or less reduced in severity when the Petersen coil is used are offset by others being increased in severity. Perhaps this is why the Petersen coil is not favoured in this country.

Mr. W. Hyland: Seeing that the authors' investigation is comparative I should like to know whether there are any impulse-voltage phenomena which cannot be considered on a *pro rata* basis.

I should be glad if the authors would say a few words in connection with the method they employed for obtaining the voltage impulses and the variations in the form of the wave-fronts and wave-tails.

Lastly, concerning the application of the research to practice, I should like to know whether the tendency has been to make transformers non-resonant by the introduction of artificial capacitances in the required ratios; or whether the original method of heavily insulating the end turns, possibly modified in the light of a greater knowledge of the voltages involved, has been adhered to as a result of the investigation.

Mr. B. Lloyd Price: The effects of impulse voltages on transformer windings depend upon the surge-impedance of the transformer and the complex impressed wave of voltage. The voltage curves reproduced in the paper show that the terminal voltage is that of the impressed wave at any given instant. The voltage to earth rises along the winding to a maximum in the vicinity of 30 % of the turns. The inter-turn p.d., or the change of voltage per turn, thus falls progressively to zero at the point of maximum voltage to earth. I have stated what may appear too obvious for remark for the reason that without oscillograph records, transients must remain a mystery to the non-mathematical and a puzzle even to many mathematicians.

Dr. T. E. Allibone, and **Messrs. D. B. McKenzie** and **F. R. Perry** (*in reply*): Bearing in mind the date at which a decision had to be taken with regard to the adoption of Petersen coil or solidly earthed neutral to the major transmission-line systems of this country, it is unlikely that that decision was influenced by considerations of the effects of impulse voltages on transformer windings connected to Petersen coils. Where coils are used there seems to be ample evidence that sparkover may take place at the neutral, and recently such an occurrence has been recorded by the oscillograph under normal service conditions. If the winding is such that it can withstand the stresses produced by flashover at the neutral, no protective measures are necessary: otherwise voltage limiting devices such as lightning arresters should be installed.

The film exhibited at the reading of our paper showed the voltage to earth at all parts of the winding at different times after the application of the impulse voltage: the ordinates were taken from a large number of oscillograms of the voltages at many points of the winding with respect to earth. The impressed voltage was not constant but decreased exponentially, and this fact is shown by the fall of voltage with time on the left-hand ordinate of the camera film: its initial value is shown as 100, and this marking persists throughout the film.

We do not think that there are any phenomena of importance which appear only at higher voltages, other, of course, than breakdown. As a result of the work described in our paper and other papers manufacturers are endeavouring to evolve the surge-proof transformer or other devices to help the transformer. "Non-resonating" principles are being tried out, but reinforcement on end-turns is still practised until a definite change can be advocated with assurance of success. Mr. Price's comment is borne out by the curves A′ and B′ of Fig. V on page 348 (vol. 80) of the discussion.

We would refer Mr. Hyland to Fig. 7 of the paper for a description of our method of producing impulse voltages. To change the wave-front we changed L_1, and to change the wave-tail we changed R_1, R_2, R_3, keeping $R_2 + R_3$ constant.

* Paper by Dr. T. E. Allibone and Messrs. D. B. McKenzie and F. R. Perry (see vol. 80, p. 117).

PROCEEDINGS OF THE INSTITUTION

922ND ORDINARY MEETING, 6TH JANUARY, 1938

Sir George Lee, O.B.E., M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 16th December, 1937, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of December, 42 donations and subscriptions to the Benevolent Fund had been received, amounting to £86. A vote of thanks was accorded to the donors.

The following list of donors to the Library was taken as read, and the thanks of the meeting were accorded to them: Air Ministry; W. Aitken; Amalgamated Wireless (Australia) Ltd.; American Embassy (Commercial Attaché); American Institute of Electrical Engineers; American Radio Relay League; American Telegraph and Telephone Co.; H. T. Aspinall, B.Sc.; Association Internationale pour L'Essai des Matériaux; Association of American Railroads; Association of Municipal Electricity Undertakings, South Africa; The Astronomer Royal; Messrs. Babcock and Wilcox, Ltd.; Messrs. Benn Bros., Ltd.; Messrs. Bennis Combustion, Ltd.; Messrs. Blackie and Sons, Ltd.; S. C. Blacktin; A. Blondel; British Broadcasting Corporation; British East African Meteorological Services; British Electrical and Allied Industries Research Association; British Engine, Boiler, and Electrical Insurance Co., Ltd.; British Standards Institution; H. G. Brown; Canadian Bureau of Statistics; Canadian Engineering Standards Association; A. Carrayrow; Carriers Publishing Co., Ltd.; Central Electricity Board; Chadwick Trust; Cold Storage and Produce Review; Comité du Centenaire d'André Marie Ampère; Messrs. Constable and Co., Ltd.; Copper Development Association; H. Cotton, M.B.E., D.Sc.; P. R. Coursey, B.Sc.; A. L. Curtis; M. E. Day; Department of Electrical Undertakings, Ceylon; Department of Scientific and Industrial Research; Departement van Verkeer en Waterstaat; A. Dover; Drawing Office Material Manufacturers' and Dealers' Association; Electric Supply Authority Engineers' Association, New Zealand; Messrs. Electric Transmission, Ltd.; Electricity Advisory Committee, New South Wales; Electricity Commissioners; Electricity Supply Commission, South Africa; Electrodepositors' Technical Society; "Engineering"; F. Ernstein; Fedération des Associations Belge d'Ingenieurs; Federation of British Industries; Messrs. John Firth and John Brown, Ltd.; General Post Office (Public Relations Department); Messrs. S. Hirzel; Home Office; F. C. Hoyle; E. Hughes, Ph.D., D.Sc.; Hydro-Electric Power Commission of Ontario; W. S. Ibbetson; Messrs. Iliffe and Sons, Ltd.; The Imperial Institute; Incorporated Municipal Electrical Association; Indian Posts and Telegraphs Department; Indian Institute of Science; Institute of Physics; International Electrotechnical Commission; International Standard Electric Corporation; International Tin Research and Development Association; Iron and Steel Institute; Messrs. Walter King, Ltd.; Messrs. Johnson and Phillips, Ltd.; Prof. A. E. Kennelly, D.Sc.; London and Home Counties Joint Electricity Authority; Messrs. Longmans, Green and Co., Ltd.; Messrs. Macdonald and Evans; Messrs. McGraw-Hill Publishing Co., Ltd.; Messrs. Macmillan and Co., Ltd.; Manchester Association of Engineers; J. W. Meares, C.I.E.; Meteorological Office; Ministry of Health and Scottish Office; Mines Department; Messrs. Mond Nickel Co., Ltd.; E. Molloy; A. I. Morgan; A. Morley, O.B.E., D.Sc.; Messrs. Mullard and Co., Ltd.; Messrs. Murex Processes, Ltd.; S. Narayan; National Electrical Manufacturers' Association; National Illumination Committee of Great Britain; Messrs. George Newnes, Ltd.; New Zealand Post and Telegraph Department; S. Noda; S. J. Patmore; L. Péter; Messrs. Sir Isaac Pitman and Sons, Ltd.; Messrs. Plastic Press, Ltd.; Rand Water Board, South Africa; Messrs. Rawlplug Co., Ltd.; J. H. Reyner, B.Sc.; Royal Alfred Observatory, Mauritius; Royal Technical College, Glasgow; A. Rubin; L. Sandicoeur; Science Museum; W. Scott; Seismograph Service Corporation; R. C. Smart; Prof. S. P. Smith, D.Sc.; Société Financière de Transports et d'Entreprises Industrielles (Sofina); Messrs. E. & F. N. Spon, Ltd.; Standards Association of Australia; A. T. Starr, M.A., Ph.D.; Surveyor General of India; Svenska Elektricitetswerks Foreningen; E. O. Taylor, B.Sc.; The Technical Press, Ltd.; W. H. Thompson; Mrs. Elihu Thomson; R. W. Todd; The Trade Publishing Co., Ltd.; D. F. Twiss, D.Sc.; Union des Syndicats de L'Électricité; Dr. H. J. Van Der Bijl, M.A., Ph.D., D.Sc.; C. E. H. Verity; Messrs. Virtue and Co., Ltd.; H. C. Widlake; Captain W. A. Williams; Wirtschaftsgruppe Elektroindustrie; A. T. Witts; and J. Wright.

A paper by Messrs. H. W. Clothier, Member, B. H. Leeson, Member, and H. Leyburn, B.Sc., Associate Member, entitled "Safeguards against Interruptions of Supply" (see page 445), was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

923RD ORDINARY MEETING, 20TH JANUARY, 1938

Sir George Lee, O.B.E., M.C., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 6th January, 1938, were taken as read and were confirmed and signed.

The President announced that the Council had

elected Mr. F. Gill, O.B.E., an Honorary Member of The Institution, and that the sixteenth award of the Faraday Medal had been made to Sir John Snell, G.B.E.

Messrs. F. L. Otter and W. C. Rose were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 228) had been duly elected and transferred.

The following papers were read and discussed: "The Design of Domestic Electric Cookers" (see page 565), by Mr. O. W. Humphreys, B.Sc.; and "Electric Cookers for Domestic Purposes, with special reference to Maintenance Costs" (see page 583), by Mr. J. N. Waite, Member.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

INSTITUTION NOTES

INDEX TO JOURNAL

Any member who proposes to bind the current volume of the *Journal* and would like to have an extra copy of the Index for filing apart from the bound volume of the *Journal* can obtain an additional copy on application to the Secretary.

LIST OF MEMBERS

A new List of Members, corrected to the 1st September, 1937, was published at the end of last year. Any member wishing to receive a copy should apply to the Secretary.

PREMIUMS

At the Annual General Meeting held on the 12th May the President announced that the Council had made the following awards of Premiums for papers during the session 1937–38:—

The Institution Premium (*value* £25).

A. D. Blumlein, B.Sc. (Eng.), C. O. Browne, N. E. Davis, and E. Green, M.Sc. — "The Marconi-E.M.I. Television System."

The Ayrton Premium (*value* £10).

H. W. Clothier, B. H. Leeson, and H. Leyburn, B.Sc. — "Safeguards against Interruptions of Supply."

The Fahie Premium (*value* £10).

F. G. Tyack — "Street Traffic Signals, with particular reference to Vehicle Actuation."

The John Hopkinson Premium (*value* £10).

W. G. Thompson, Ph.D., B.Sc. — "Recent Progress in Power Rectifiers and their Applications."

The Paris Exhibition (1881) *Premium* (*value* £10).

J. S. Pickles, B.Sc. Tech. — "Rural Electrification."

A Premium (*value* £10).

E. T. Norris — "The Moving-Coil Voltage Regulator."

A Premium (*value* £5).

D. J. Bolton, M.Sc. — "Electricity Demand and Price."

A Premium (*value* £5).

A. H. Davis, D.Sc. — "An Objective Noise Meter for the Measurement of Moderate and Loud, Steady and Impulsive Noises."

A Premium (*value* £5).

C. E. Fairburn, M.A. — "The Trend of Design of Electric Locomotives."

A Premium (*value* £5).

O. W. Humphreys, B.Sc. — "The Design of Domestic Electric Cookers."

A Premium (*value* £5).

W. Maurice — "The Evolution of the Miner's Electric Hand-Lamp."

A Premium (*value* £5).

J. N. Waite — "Electric Cookers for Domestic Purposes, with special reference to Maintenance Costs."

An Overseas Premium (*value* £10).

V. K. Zworykin, Ph.D., G. A. Morton, Ph.D., and L. E. Flory — "Theory and Performance of the Iconoscope."

An Overseas Premium (*value* £5).

Prof. B. L. Goodlet, M.A. — "A Note on Voltage Instability in Testing Equipment."

Wireless Section Premiums

A Premium (*value* £10).

J. Bell, B.Sc., J. W. Davies, and B. S. Gossling, M.A. — "High-Power Valves: Construction, Testing, and Operation."

A Premium (*value* £10).

A. J. Gill, B.Sc.(Eng.), and S. Whitehead, M.A., Ph.D. — "Electrical Interference with Radio Reception."

A Premium (*value* £10).

T. C. Macnamara and D. C. Birkinshaw, M.A. — "The London Television Service."

Meter and Instrument Section Premiums

A Premium (*value* £10).

C. W. Hughes, B.Sc. "Organization of a Meter Test Department of a Large Supply Undertaking, with special reference to the Electricity Supply (Meters) Act, 1936."

A Premium (*value* £10).

T. A. Ledward "Some Polarization Phenomena in Magnetic Materials, with special reference to Nickel-Iron Alloys."

A Premium (*value* £10).

K. J. R. Wilkinson, B.Sc. "Recurrent-Surge Oscillographs, and their Application to Short-time Transient Phenomena."

Transmission Section Premiums

The Sebastian de Ferranti Premium (*value* £20).

J. L. Miller, Ph.D., D.Eng., and J. M. Thomson, Ph.D. "The Surge Protection of Power Transformers."

A Premium (*value* £10).

S. Whitehead, M.A., Ph.D., and E. E. Hutchings, B.Sc. (Eng.) "Current-Rating of Cables for Transmission and Distribution."

The awards for papers read before the Students' Sections will be published later.

COUNCIL'S NOMINATIONS FOR ELECTION TO THE COUNCIL

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-President, Honorary Treasurer, and Ordinary Members of Council, on the 30th September, 1938:—

President. (*One Vacancy.*)
A. P. M. Fleming, C.B.E., D.Eng., M.Sc.

Vice-President. (*One Vacancy.*)
Prof. C. L. Fortescue, O.B.E., M.A.

Honorary Treasurer. (*One Vacancy.*)
W. McClelland, C.B., O.B.E.

Ordinary Members of Council.
Members. (*Three Vacancies.*)

P. Dunsheath, O.B.E., M.A., D.Sc.
Prof. R. O. Kapp, B.Sc.
A. P. Young, O.B.E.

Associate Member. (*One Vacancy.*)
L. G. Brazier, Ph.D., B.Sc.

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register. The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of The Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

OVERSEAS MEMBERS AND THE INSTITUTION

During the period 1st February to 31st May, 1938, the following members from overseas called at The Institution and signed the "Attendance Register of Overseas Members":—

Akhurst, F. K. (*Wellington, N.Z.*).
Bennett, P. T. (*N'Kala, N. Rhodesia*).
Brand, F. (*Muar, Malaya*).
Coates, A. G. (*Jerusalem*).
Colombi, J. S. B. (*Shanghai*).
Croxford, M. P., B.Sc. (*Perak, F.M.S.*).
Davies, N. C. (*Colombo*).
Dawson, M. W. (*Bukuru, Nigeria*).
De Kretser, H. E. S. (*Colombo*).
Drake, H. H. (*Burnpur, India*).
Gardam, J. R. W. (*Perth, W. Australia*).
Grant, I. C. (*Buenos Aires*).
Hall, J. O. (*Lagos, Nigeria*).
Havart, R. F. (*Khodaung, Burma*).
Henderson, D. H. P. (*Calcutta*).
Hogben, E. J., M.A. (*Calcutta*).
Howard, H. G. (*Madras*).
Larard, F. J. (*Sentul, F.M.S.*).
L'Estrange, W. M. E. (*Brisbane*).
McCutcheon, I. W. (*Wellington, N.Z.*).
Mill, H. (*Pretoria*).
Millward, G. R. (*Atbara, Sudan*).
Morgan, J. R. H. (*Ayr, Queensland*).
Pallot, C. F. (*Cairo*).
Patel, J. G. (*Ahmedabad, India*).
Phillips, C. G. R. (*Kuala Lumpur, F.M.S.*).
Phillips, W. A. G. (*Calcutta*).
Pope, H. C. G. (*Salisbury, S. Rhodesia*).
Redpath, F. R. (*Wellington, N.Z.*).
Retief, D. P. J., B.A., B.Sc.(Eng.) (*Cape Town*)
Shepherd, S. A. (*Hobart*).
Smyth, J. H., B.Sc. (*Bombay*).
Steel, C. S. (*Calcutta*).
Tyrer, A. R. A. (*Aden*).
Veith, F. S. (*Zürich*).
Waddle, R. A., B.Sc. (*Singapore*).
Watson, S. R. (*Bombay*).
Wilson, J. Haynes, M.C. (*Shanghai*).

PROCEEDINGS OF THE WIRELESS SECTION

140th Meeting of the Wireless Section, 5th January, 1938

Mr. T. Wadsworth, M.Sc., chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 1st December, 1937, were taken as read and were confirmed and signed.

A paper by Mr. D. A. Bell, B.A., B.Sc., Graduate, entitled " A Theory of Fluctuation Noise " (see page 522), was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

12TH INFORMAL MEETING OF THE WIRELESS SECTION, 25TH JANUARY, 1938.

Mr. T. Wadsworth, M.Sc., chairman of the Section, took the chair at 6.30 p.m.

The minutes of the Informal Meeting held on the 23rd November, 1937, were taken as read and were confirmed and signed.

A discussion, opened by Mr. L. H. Bedford, M.A., took place on " Cathode-Ray Tubes for Wireless Purposes."

At the conclusion of the discussion a vote of thanks was accorded to Mr. Bedford for his introductory remarks.

PROCEEDINGS OF THE METER AND INSTRUMENT SECTION

72ND MEETING OF THE METER AND INSTRUMENT SECTION, 5TH NOVEMBER, 1937

Mr. G. F. Shotter, the retiring chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 7th May, 1937, were taken as read and were confirmed and signed.

Mr. Shotter announced the Council's award of Premiums (see vol. 80, page 678) for papers presented to the Section during the session 1936–37. He then vacated the chair, which was taken by the new chairman, Mr. H. Cobden Turner.

A vote of thanks to Mr. Shotter for his services as chairman during the session 1936–37, proposed by Mr. W. Phillips and seconded by Mr. A. J. Pitt, was carried with acclamation.

Mr. Cobden Turner then delivered his Inaugural Address (see page 20).

A vote of thanks to the chairman for his Address, proposed by Mr. R. S. J. Spilsbury, B.Sc.(Eng.), and seconded by Mr. L. C. Benton, was carried with acclamation.

73RD MEETING OF THE METER AND INSTRUMENT SECTION, 10TH DECEMBER, 1937

Mr. H. Cobden Turner, chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 5th November, 1937, were taken as read and were confirmed and signed.

A paper by Mr. C. W. Hughes, B.Sc., Associate Member, entitled " Organization of a Meter Test Department of a Large Supply Undertaking, with special reference to the Electricity Supply (Meters) Act, 1936 " (see page 410), was read and discussed.

A vote of thanks to the author, moved by the chairman, was carried with acclamation.

74TH MEETING OF THE METER AND INSTRUMENT SECTION, 7TH JANUARY, 1938

Mr. H. Cobden Turner, chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 10th December, 1937, were taken as read and were confirmed and signed.

The following papers were read and discussed: " The Calibration of Sphere-Gaps with Impulse Voltages " (see page 645), by Messrs. R. Davis, M.Sc., Associate Member, and G. W. Bowdler, M.Sc.; and " The Calibration of the Sphere Spark-Gap for Voltage Measurement up to One Million Volts (Effective) at 50 Cycles " (see page 655), by Messrs. F. S. Edwards, B.Sc., Associate Member, and J. F. Smee.

A vote of thanks to the authors, moved by the chairman, was carried with acclamation.

PROCEEDINGS OF THE TRANSMISSION SECTION

22ND MEETING OF THE TRANSMISSION SECTION, 17TH NOVEMBER, 1937

Dr. P. Dunsheath, O.B.E., M.A., the retiring chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 29th April, 1937, were taken as read and were confirmed and signed.

The chairman announced the Council's award of Premiums (see vol. 79, page 678) for papers read before the Section during the session 1936–37.

Dr. Dunsheath then vacated the chair, which was taken by the new chairman, Mr. J. L. Eve.

A vote of thanks to Dr. Dunsheath for his services as chairman during the session 1936–37, proposed by Mr. S. R. Siviour and seconded by Mr. H. J. Allcock, was carried with acclamation.

Mr. Eve then delivered his Inaugural Address (see page 26).

A vote of thanks to the chairman for his Address, proposed by Dr. Dunsheath and seconded by Mr. N. K. Bunn, was carried with acclamation.

23RD MEETING OF THE TRANSMISSION SECTION, 15TH DECEMBER, 1937

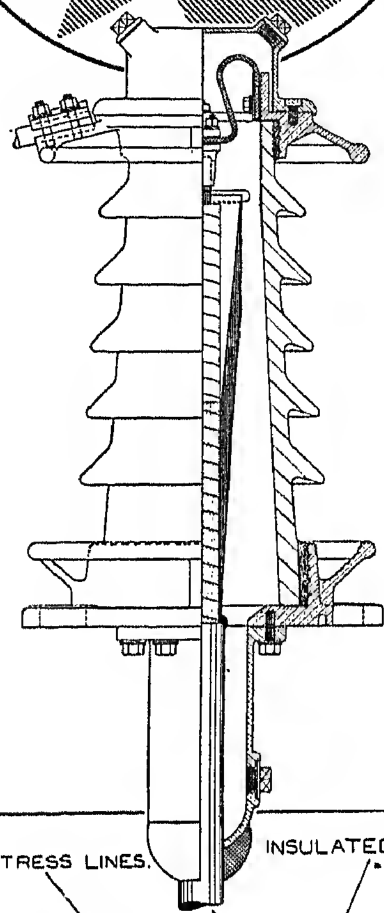
Mr. J. L. Eve, chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 17th November, 1937, were taken as read and were confirmed and signed.

A paper by Messrs. H. Willott Taylor, Associate Member, and P. F. Stritzl, D.Sc.Tech., entitled " Line Protection by Petersen Coils, with special reference to Conditions prevailing in Great Britain" (see page 387), was read and discussed.

A vote of thanks to the authors, moved by the chairman, was carried with acclamation.

CONDENSER CONES
FOR
SUPERTENSION CABLE TERMINATION RELIABILITY



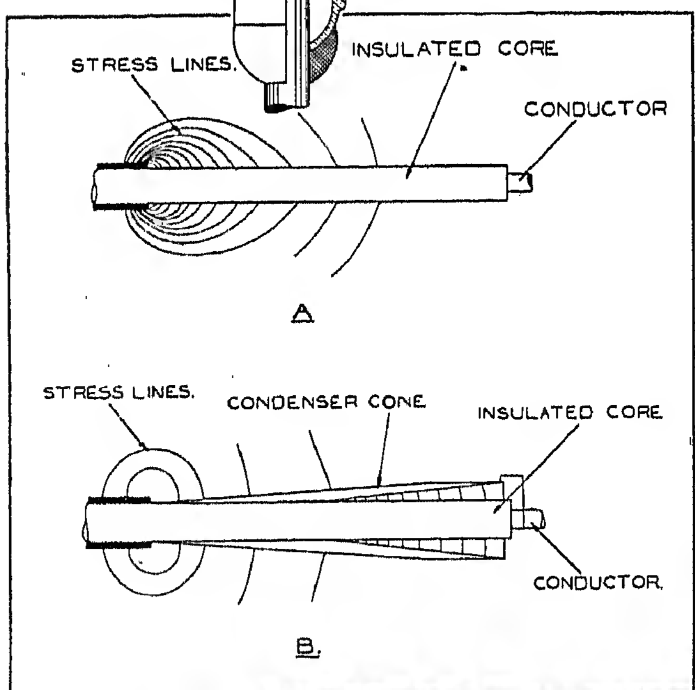
Supertension Sealing End, fitted with Condenser Cone.

ANYONE associated with the development, testing installation or maintenance of supertension power cables readily appreciates the paramount importance of the problem of their termination.

Any satisfactory cable termination must reconcile the mathematical and engineering aspects and possess the essential qualities of reliability in service, ease of installation and economical cost.

The CONDENSER CONE fulfils all these requirements and represents a very definite advance in supertension cable termination technique.

Full details will gladly be sent upon request.



The distribution of electrical stress at (A) a bare end, and, (B) the same end after fitting with a condenser cone; illustrating how stress concentration is thus eliminated.

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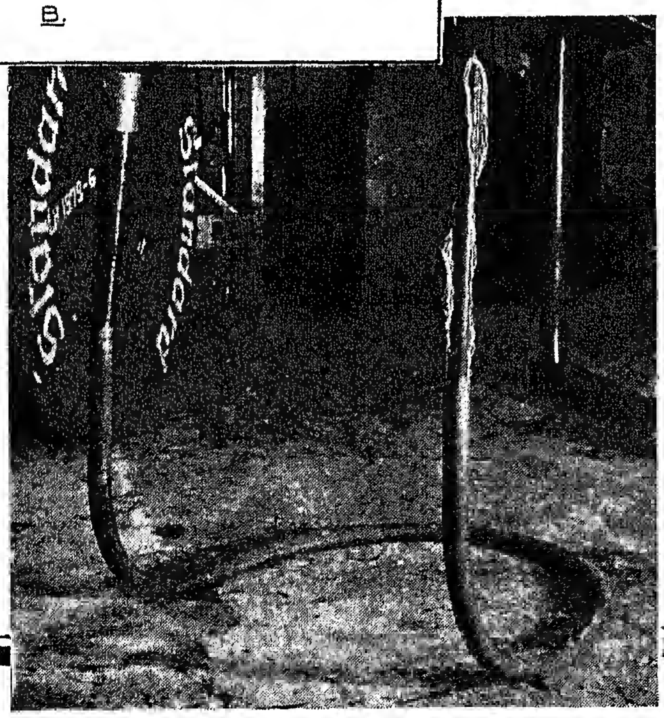
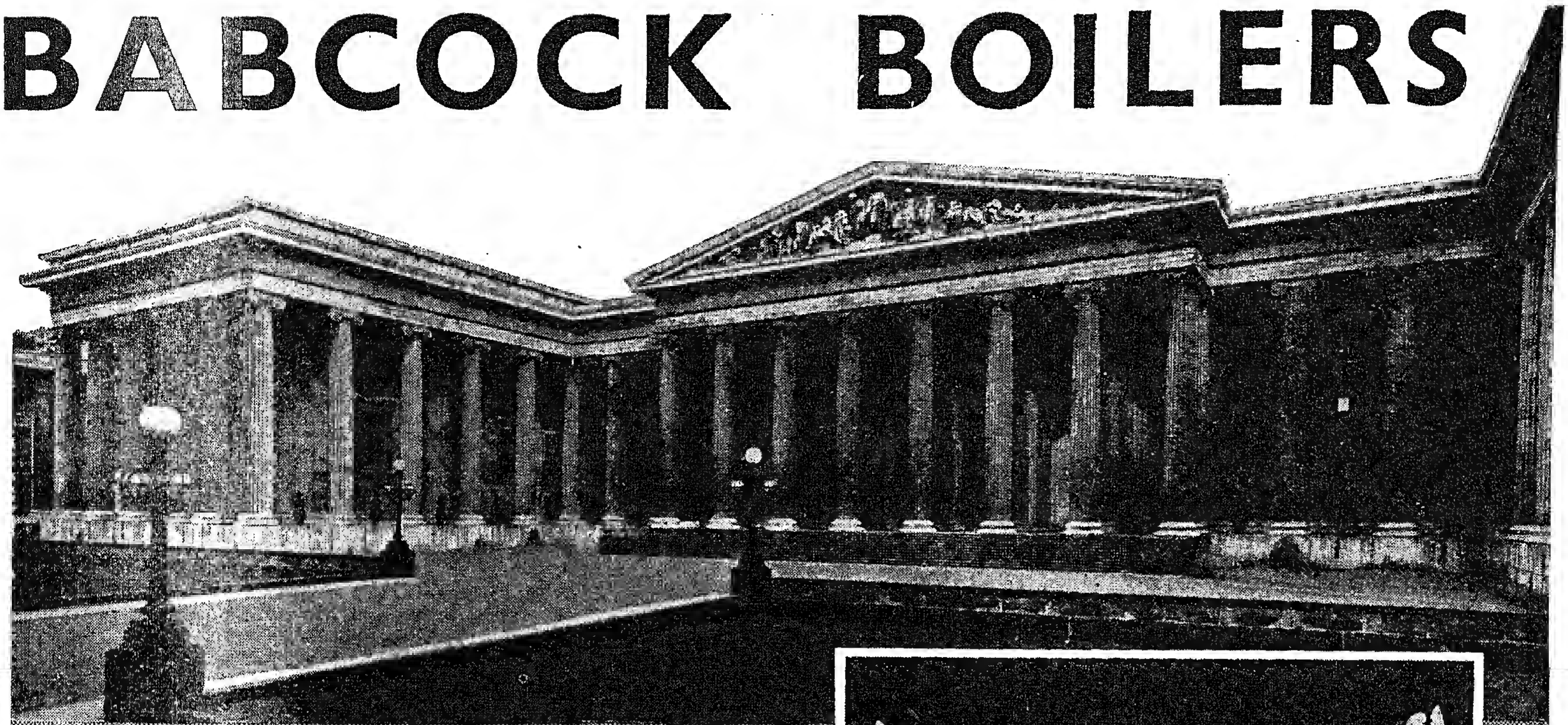
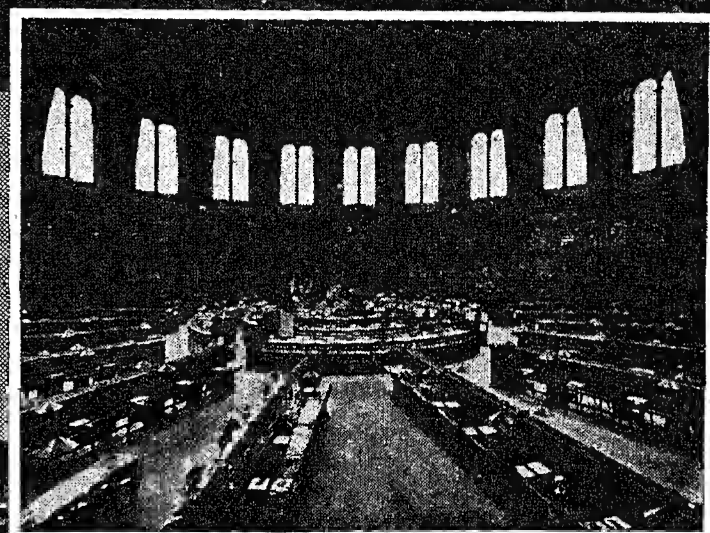


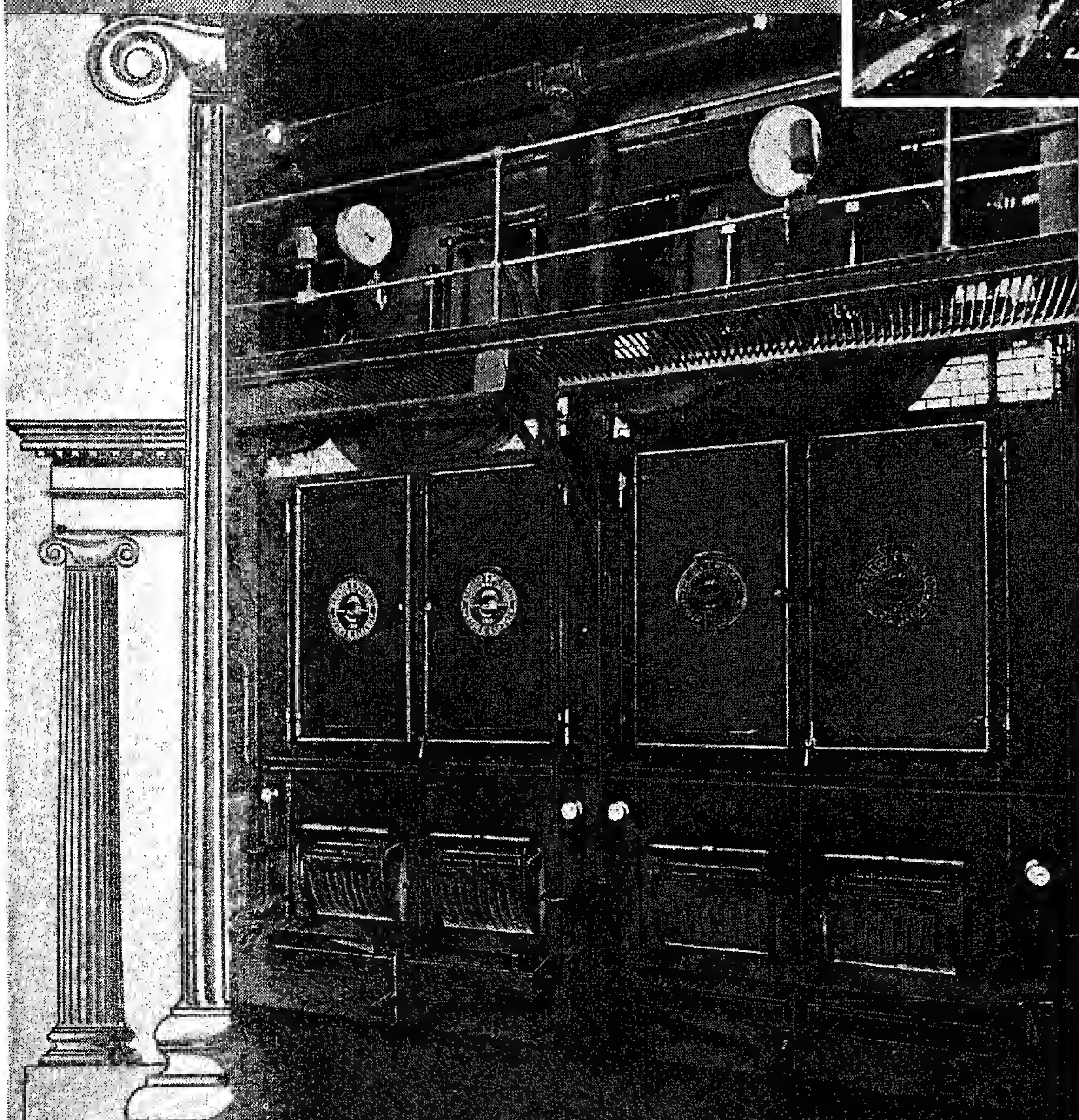
Factory demonstration of Condenser Cone. Unprotected end flashing over. Protected end giving neither audible nor visible sign of discharge.

BABCOCK BOILERS



at the BRITISH MUSEUM





AT the order of H.M. Office of Works two Babcock & Wilcox Boilers, each of 2,255 square feet heating surface, have been installed in the British Museum for central heating purposes. These boilers are hand-fired and supply steam at 160 lbs. per square inch.

The illustrations show the exterior of the Museum, the Reading Room and the Babcock Boilers.

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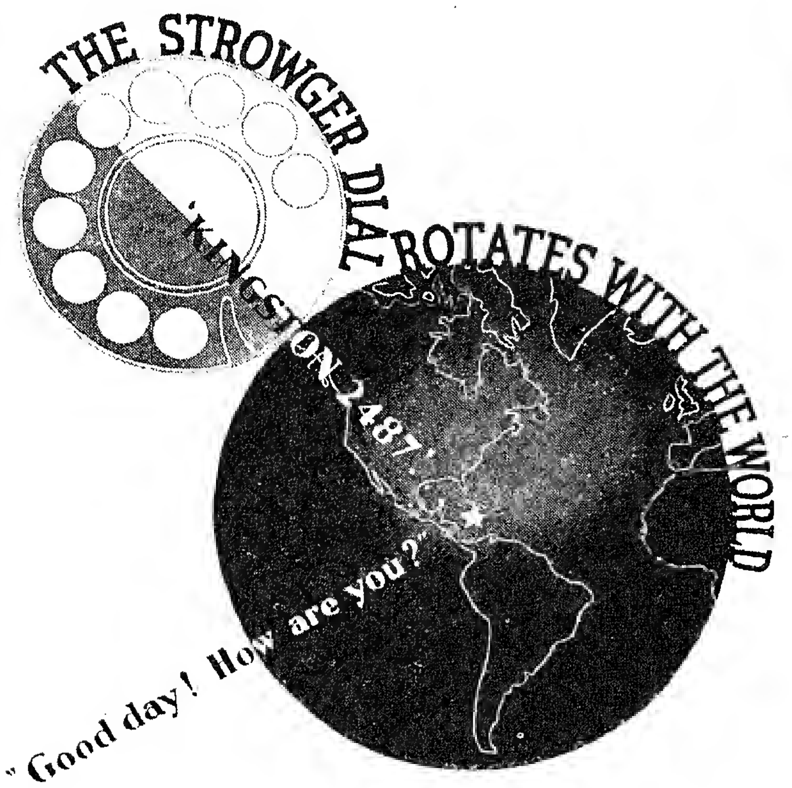

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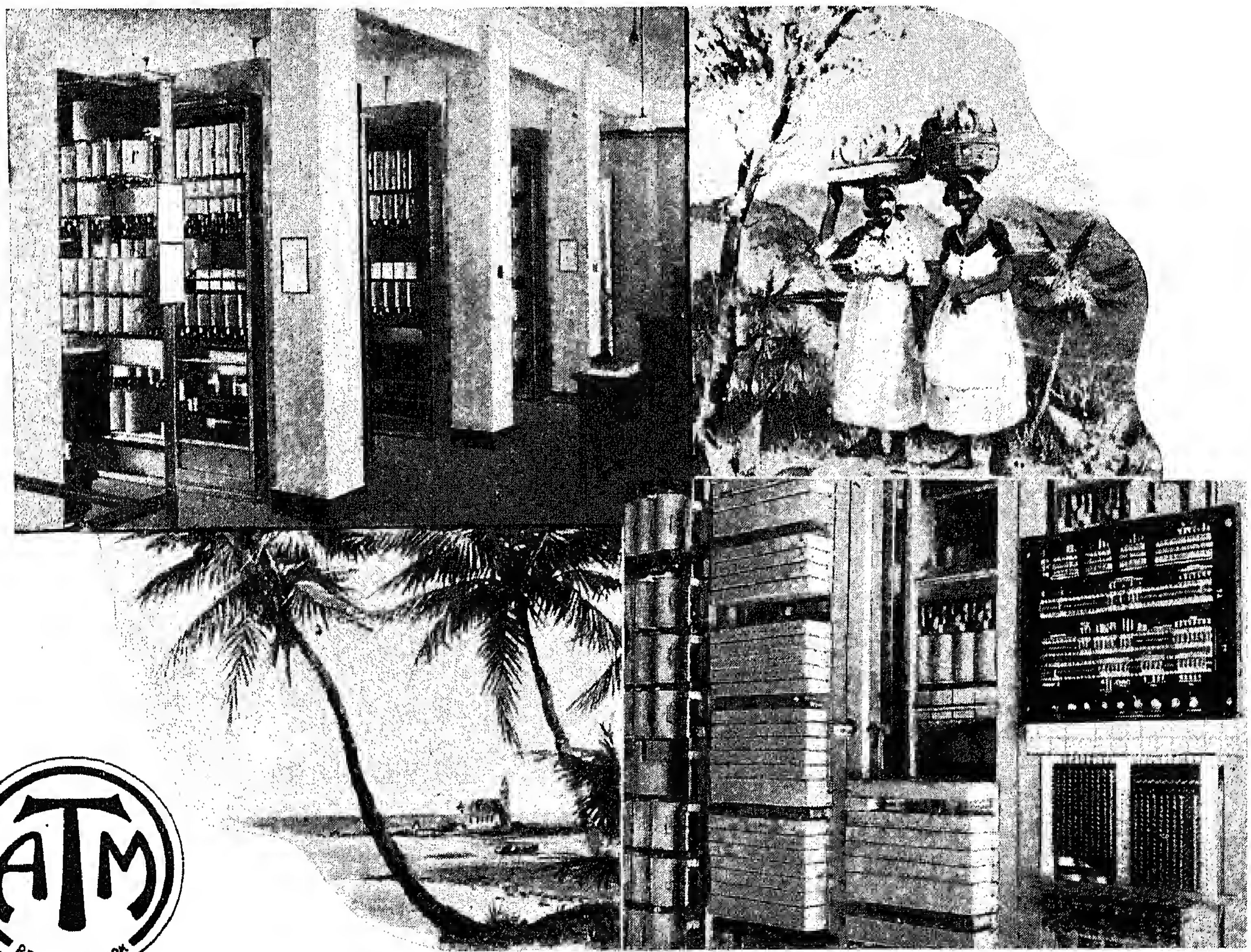

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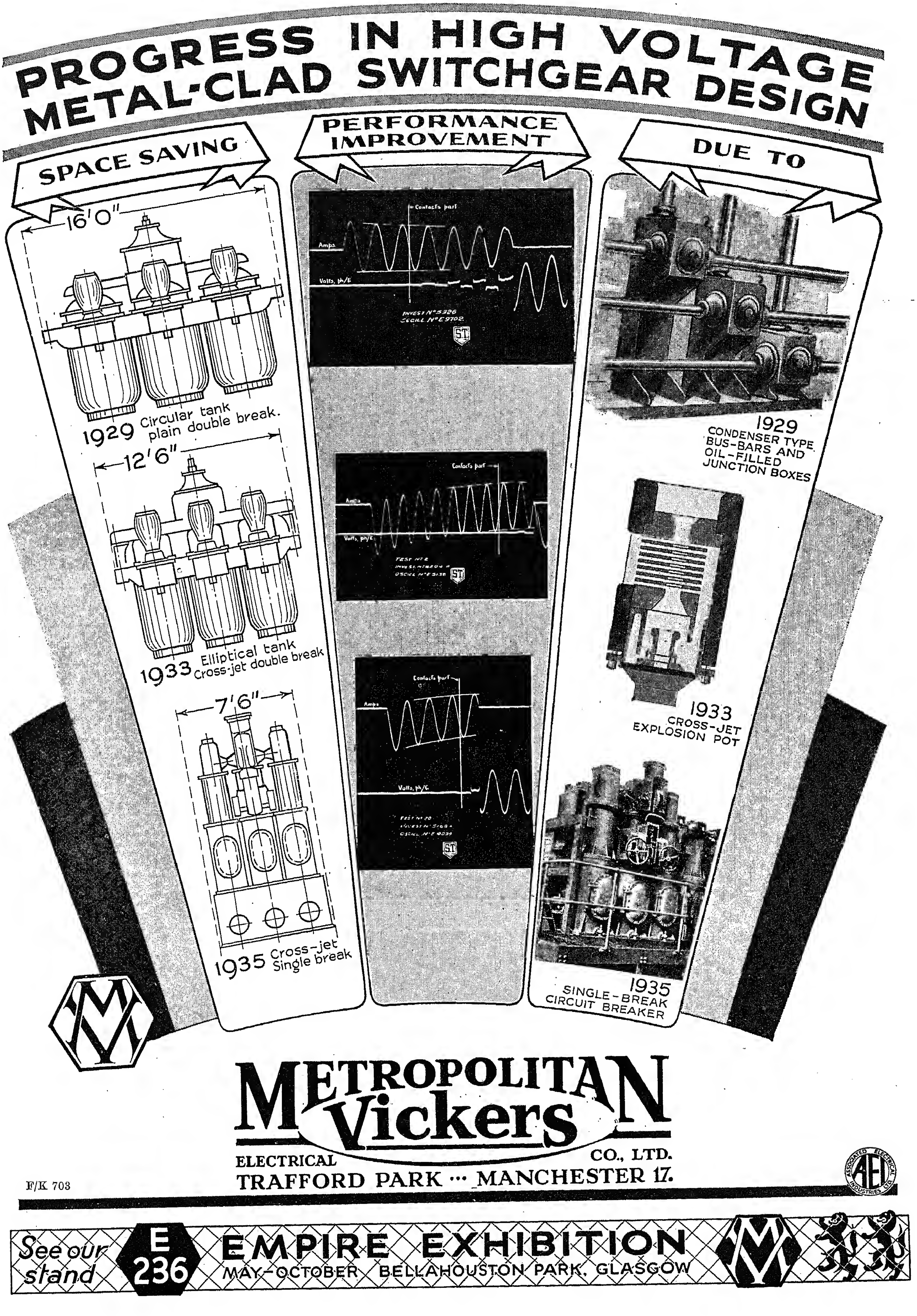
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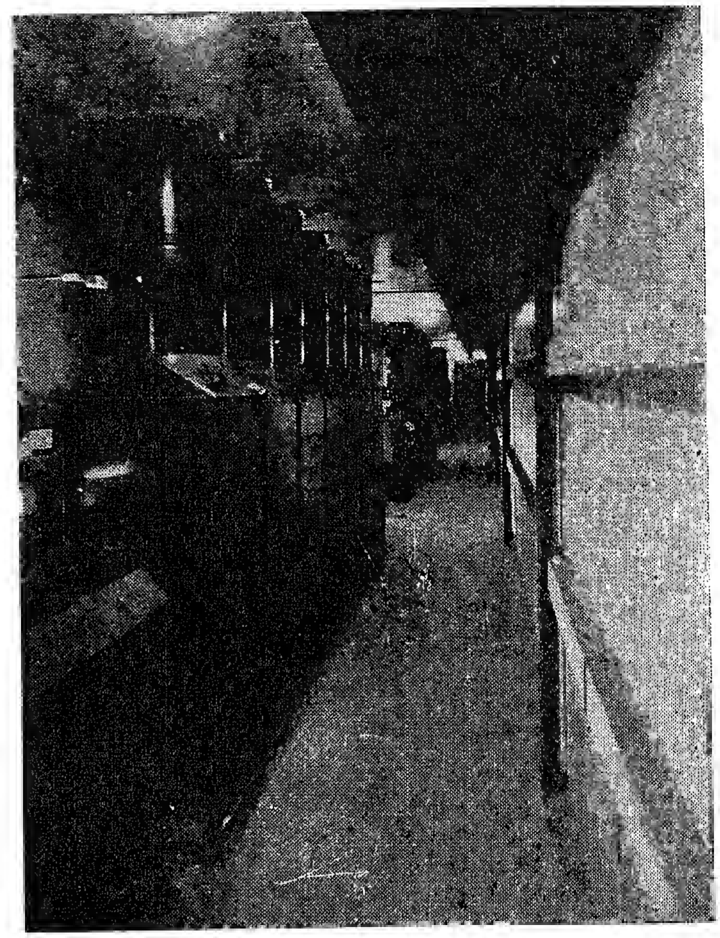

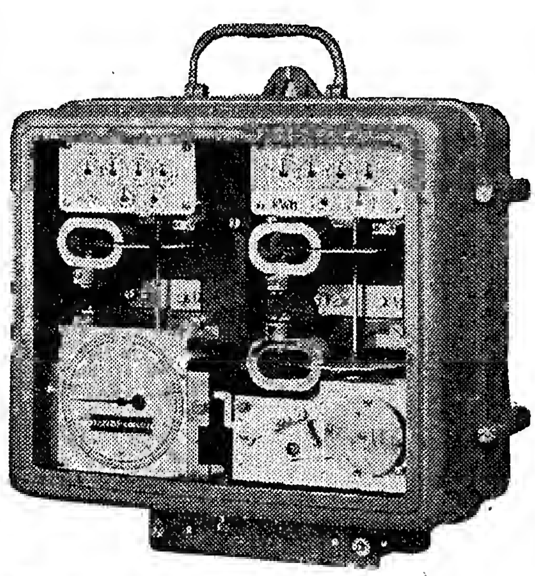

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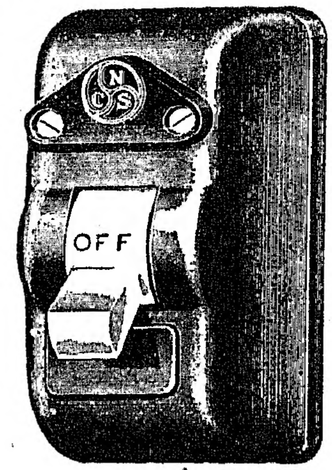

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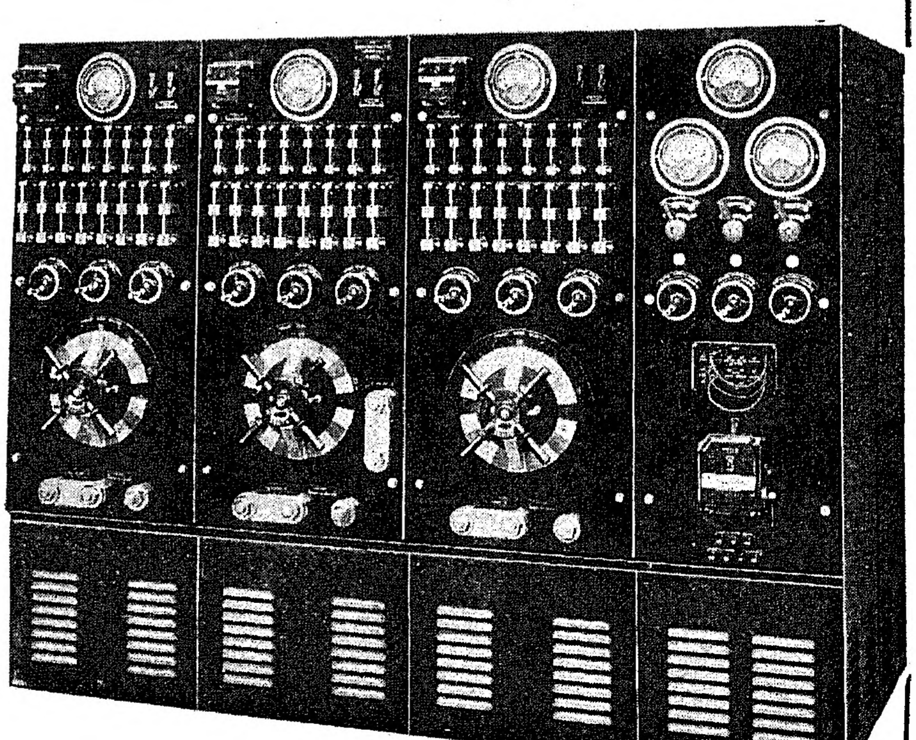

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